Report No. FHWA-RD-77-6

CANDE USER MANUAL

October 1976

Final Report

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Springfield, Virginia 22161

Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D. C. 20590

NOTICE

Technical Report Documentation Page

1. Report No. FHWA-RD-77-6	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CANDE USER MANUAL		5. Report Date October 1976
		6. Performing Organization Code
7. Author(s) M. G. Katona and J. M. Smith		8. Performing Organization Report No.
9. Performing Organization Name and Address Civil Engineering Laboratory Naval Construction Battalion Center Port Hueneme, California 93043		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. I.A. 3-1170
12. Sponsoring Agency Name and Address Office of Research U.S. Federal Highway Administration Washington, D.C. 20590		13. Type of Report and Period Covered Final Report - User Manual 1973-1976
		14. Sponsoring Agency Code 35I3-112

15. Supplementary Notes

Companion documents are FHWA-RD-77-5 "Final Report," and FHWA-RD-77-7 "System Manual."
Project Manager: G. W. Ring, HRS-14

16. Abstract

The manual contains input instructions, recommendations, and illustrations for a new computer program for culvert analysis and design (CANDE). The program is user-oriented in FORTRAN language. In three parts, Part 1 of the manual is a brief summary of the CANDE program, Part 2 provides formatted input instructions for data cards along with extensive commentaries and recommendations, while Part 3 contains example problems covering a wide range of potential applications and illustrating input/output features of CANDE.

17. Key Words culvert computer program User Manual	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 155	22. Price

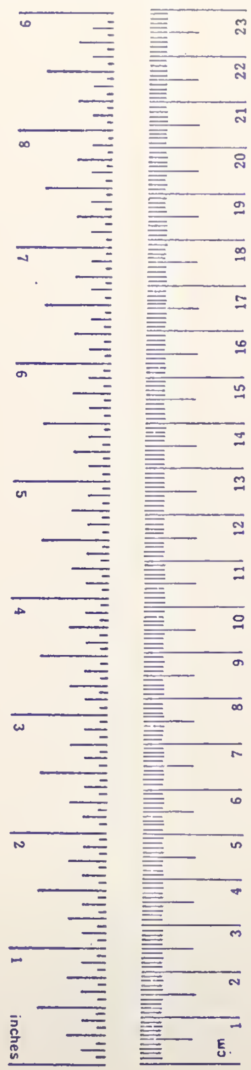
CONTENTS

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

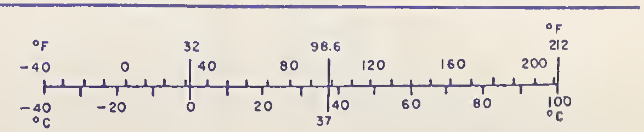
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286. Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



INTRODUCTION

This manual contains input instructions, recommendations, and illustrations for using a new culvert analysis/design methodology, called CANDE (Culvert ANalysis and DEsign). CANDE is a user-oriented, FORTRAN computer program employing state-of-the-art analytical methods for designing and analyzing the structural integrity of buried pipe culverts.

For convenience and clarity, this manual is divided into three parts. Part I is a brief summary of the scope of the CANDE program. Part II provides formated input instructions for data cards along with extensive commentaries and recommendations. Part III contains example problems covering a wide range of potential applications and illustrating input/output features of CANDE. For detailed developments the reader is referred to the companion documents:

- CANDE: Engineering Manual A Modern Approach for the Structural Design and Analysis of Buried Cylinders, by M. G. Katona et al. Civil Engineering Laboratory, Port Hueneme, CA, ________ 1976 (final technical report to Federal Highway Administration)

- CANDE: System Manual, by M. G. Katona and J. M. Smith. Port Hueneme, CA, ________ 1976 (Report to Federal Highway Administration)

PART I

CANDE OVERVIEW

CANDE offers a choice of three solution levels together with a choice of five pipe types for designing and/or analyzing buried pipe culverts. The solution levels range from an elasticity solution to a general finite element solution, which enables the engineer to select a degree of rigor and cost commensurate with the project at hand. The pipe types include corrugated steel, corrugated aluminum, reinforced concrete, plastic pipe, and basic (nonstandard).

Figure I-1 presents a schematic overview of CANDE that shows the three principal areas: the main control area at top, the pipe library at bottom left, and the solution library at bottom right. The main control area reads the problem control input and then acts as a switchboard by shifting information back and forth between the pipe library and the solution library.

To start each problem, three fundamental selections are required by the user: (1) execution mode, (2) solution level, and (3) pipe type.

Execution mode is the decision between design or analysis. Analysis means a particular pipe soil system is completely defined and then solved by the chosen solution level. Output consists of the structural responses (displacements, stresses, strains) as well as an evaluation of the pipe performance in terms of factors-of-safety against potential modes of failure.

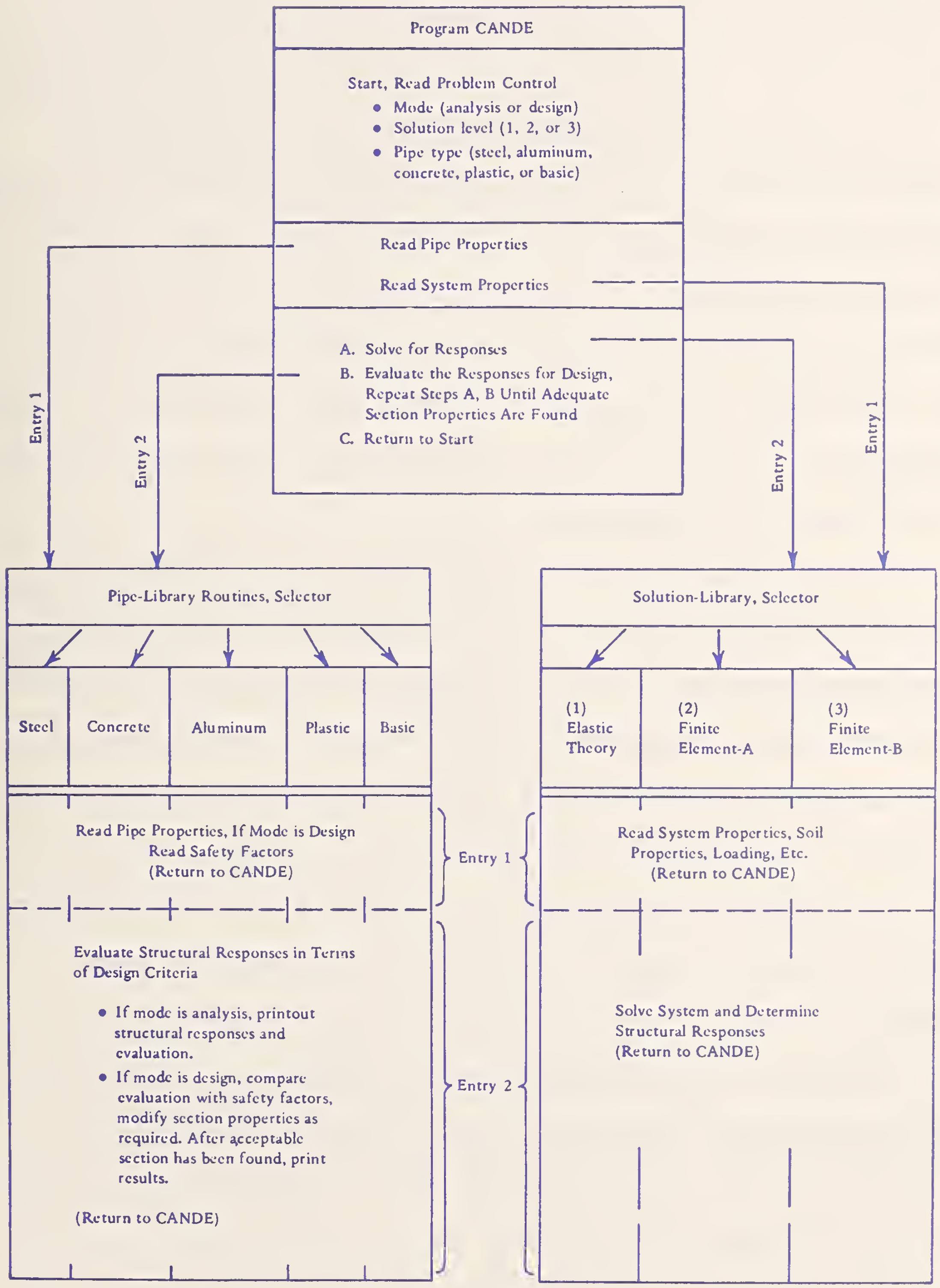


Figure I-1. Schematic diagram for CANDE.

The alternative execution mode, design, requires the same input definition except the pipe wall geometrical section properties will be unknown. Instead, desired safety factors are input, and CANDE achieves a design by a direct search approach. That is, a series of analyses are performed such that an initial trial section is successively modified until the desired safety factors are achieved. Design output includes required wall properties, actual factors of safety, and structural responses. Naturally, the required wall properties depend on the pipe type. For example, the properties for metal pipes are given in corrugation and gage sizes, while the reinforced concrete pipe properties are given in wall thickness and steel area.

The three solution levels in the solution library correspond to sucessively increased levels of analytical power and sophistication. The successive increase in analytical power is accompanied by an increase in solution costs. All solution levels assume plane strain geometry and are cast in incremental form to simulate incremental construction.

Level 1 is an enhanced elasticity solution applicable for round pipes deeply buried in homogeneous soil. Levels 2 and 3 share a common finite element methodology and only differ on the manner of input — automatic or manual. Level 2 provides a ''canned'' finite element mesh applicable for most symmetric culvert installations, including trench and embankment conditions. Level 3 permits consideration of any arbitrary culvert configurations; however, the finite element mesh model must be defined by the user.

Table I-1 summarizes the analytical features and limitations of each solution level along with an indication of input requirements and computer running time.

The CANDE pipe library currently contains subroutines for corrugated steel, corrugated aluminum, reinforced concrete, and smooth wall plastic pipe. In addition a subroutine called ‘‘BASIC’’ allows for description of nonstandard pipes; however, this routine is only applicable to analysis problems. The pipe subroutines service all three solution levels and are the key control areas of CANDE. They perform four operations: (1) read pipe input data, (2) modify pipe properties for nonlinear responses, (3) evaluate pipe safety factors, and if in design mode, (4) update section properties of pipe wall. Table I-2 summarizes the basic characteristics of each pipe subroutine.

The foregoing view of the CANDE program illustrates the ‘‘mix-and-match’’ features of CANDE. That is, any pipe type from the pipe library can be matched with any solution level from the solution library, and the pair can be run in either a design or analysis mode. Little or nothing has been said about the various technical options, such as, incremental construction, nonlinear soil laws, friction interface models, nonlinear pipe models, and other modeling features. These capabilities will be discussed in the appropriate sections of the user instructions (Part II), and they are discussed in depth in the engineering manual.

Table I-1. Capabilities and Limitations of CANDE Solution Levels

Characteristics	Level 1 (Elasticity)	Level 2 (Finite Element With Auto Mesh)	Level 3 (Finite Element With User Mesh)
Pipe shapes	Round	Round; vertical ellipse; horizontal ellipse; other[a]	Any open or closed pipe section
Soil zones	Homogeneous throughout	In-situ; backfill; bedding; packing; other[a]	Up to ten different soil zones may be defined
Stress-strain models for soil zones	Linear; overburden dependent	Linear; overburden dependent; fully non-linear	Linear; overburden dependent; fully non-linear
Installation type represented	Embankment	Embankment; trench; other[a]	User defined configuration
Symmetry conditions	Double symmetry about vertical and horizontal axis	Symmetric about vertical axis	Arbitrary boundary conditions and symmetry
Load representations of soil	Incremented overburden	Incremented overburden; gravity load construction increments (5)	Incremented overburden; gravity load construction lifts, up to 10 max
Load representation of live loads	Equivalent overburden	Equivalent overburden; strip loading[a]	Equivalent overburden; strip loading
Pipe-soil interface	Slip; no slip	Slip; no slip; friction; separation	Slip; no slip; friction; separation[b]
Number of input cards[c]	5 to 10	6 to 11	50 to 500

[a] Level 2 is provided with a ‘‘porthole’’ that allows selective modifications and inputs to canned mesh.

[b] Interface model for Level 3 also applies to soil-soil interfaces.

[c] Computer execution time is typically 10 to 20 times longer for Levels 2 and 3 than for Level 1.

Table I-2. Characteristics of Pipe

Type of Pipe	Material Stress-Strain Models	Design/Evaluation Criteria	Design Output
Corrugated steel	Linear; yield-hinge theory; bilinear stress-strain	Excessive deflection; thrust yielding; elastic buckling[a]	List of required gage thickness for each standard steel corrugation size
Corrugated aluminum	Linear; yield-hinge theory; bilinear stress-strain	Excessive deflection; thrust yielding; elastic buckling[a]; outer fiber strain rupture	List of required gage thickness for each standard aluminum corrugation size
Reinforced concrete	Concrete cracking and nonlinear compression; yielding of steel reinforcement	Concrete crushing; steel yielding; concrete shear stress; crackwidth, 0.01 in.	Required steel area for double circular or elliptical reinforcement cages; required wall thickness
Smooth wall plastic	Linear	Excessive deflection; outer fiber stress; elastic buckling	Wall thickness
Basic	Linear	No design, analysis only	No design, analysis only

[a]Buckling prediction is an approximation external to the solution levels.

PART II

INPUT INSTRUCTIONS AND COMMENTARIES

For each problem, input data must be prepared in accordance with instructions from three separate sections. The purpose of each section is:

Section A – Master control.

Section B – Pipe-type definition. This section is subdivided into: corrugated steel, corrugated aluminum, reinforced concrete, plastic, and basic.

Section C – Solution level system definition. This section is subdivided into: Level 1 (modified elasticity solution), Level 2 (finite element solution, automated), and Level 3 (finite element solution, standard).

These sections are presented in order with the subsections identified by name. Data card input instructions are grouped for each subsection, followed by a narrative commentary. The input data are keyed to the commentary by numbers in the right-hand column. Each problem must begin at Section A and follow the instructions through Section C.

SECTION A — MASTER CONTROL CARD

Input

Card 1A. Master control card (one card per problem):

Columns (format)	Variable (units)	Entry Description	Note
01-06 (A4,2X)	XMODE (word)	Word defining program mode, = ANALYS, denotes analysis problem = DESIGN, denotes design problem = STOP, program terminates, last card in deck	(1)
08-08 (I1)	LEVEL	Defines solution level to be used, = 1, denotes elasticity solution = 2, denotes finite element solution with automated mesh = 3, denotes finite element solution with user-defined mesh.	(2)
10-15 (A4,2X)	PTYPE (word)	Defines pipe type to be used, = STEEL, denotes corrugated steel = ALUMIN, denotes corrugated aluminum = CONCRE, denotes reinforced concrete = PLASTI, denotes smooth plastic = BASIC, denotes arbitrary pipe, for analysis only	(3)
17-76 (15A4)	HED (words)	User defined heading of problem to be printed with output	
77-78 (I2)	NPMAT	Number of pipe elements; only required when LEVEL = 3	
79-80 (I2)	NPPT	Number of pipe nodes; only required when LEVEL = 3	

*** GO TO SECTION B ***

Commentary

(1) The decision of design or analysis is controlled by specifying the variable XMODE. Analysis implies all system and pipe properties are known, and the objective is to evaluate the pipe performance. Design implies the pipe wall section properties are unknown, and that they will be the object of the design search. Note, the program will continue to execute problems back-to-back until XMODE = STOP is encountered.

(2) Selection of a solution level is a question of what degree of detail is desired and how much cost and time is it worth. Level 1 is quick and comparatively simple, whereas Level 3 is detailed and sophisticated. Table I-1 of Part I summarizes the scope of each solution level, and Section C of Part II provides additional detail. As a general rule of thumb, one should use the solution level commensurate with the confidence in assumed values for loading, soil properties, geometry and other culvert aspects.

For many common design problems, Level 1 is commensurate with knowledge of the pipe-soil system and is a good design tool. However, for shallow burial depths, i.e., less than one radii of cover, Level 1 should not be used.

Level 2, which is considered the workhorse of CANDE, is applicable to most design and analysis problems. Input is relatively simple, yet a great deal of modeling detail is possible.

A special ''extended'' feature of Level 2 allows selective modification of the standard Level 2 mesh.

Level 3 requires familiarity with the finite element method for proper modeling of the pipe-soil system. This level is required for nonstandard problems, such as asymmetric loading and geometry. Level 3 unleashes the full power of the finite element method; however, a considerable amount of time is required to define input and ''debug'' the mesh.

(3) Table I-2 of Part I summarizes characteristics of each pipe type. Only one pipe type can be selected for each problem. To obtain a comparative study of one pipe type versus another, simply resubmit the data deck with the new PTYPE and corresponding Section B data cards.

If no pipe elements are desired (only possible in Level 3), PTYPE must be defined as BASIC, and NPMAT and NPPT must be set to zero.

SECTION B — PIPE TYPES

Go to the subsection that corresponds to the chosen pipe type:

- Corrugated steel
- Corrugated aluminum
- Reinforced concrete
- Plastic
- Basic

Commentaries are included after the input instructions for each pipe type.

Corrugated Steel Input (Cards 1B, 2B)

Card 1B. Pipe size and material properties:

Columns (format)	Variable (units)	Entry Description	Note
01-05 (I5)	NONLIN	Denotes type of material behavior = 0, linear stress strain-law = 1, yield-hinge theory = 2, bilinear stress-strain law	(1)
06-15 (F10.0)	PDIA (in.)	Pipe diameter, average	(2)
16-25 (F10.0)	PE (psi)	Elastic Young's modulus of pipe material, Default = 30 x 10^6 psi	
26-35 (F10.0)	PNU	Poisson's ratio of pipe material, Default = 0.3	
36-45 (F10.0)	PYIELD (psi)	Yield stress of pipe material, Default = 33,000 psi	
46-55 (F10.0)	PDEN (pci)	Density of material for body weight; only applies to Levels 2 and 3, Default = 0.0	
56-65 (F10.0)	PE2 (psi)	Modulus of upper portion of bilinear stress-strain curve; used only with NONLIN = 2 Default = 0.0	(3)

Card 2B. For analysis only, wall properties:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	PA ($in.^2$/in.)	Area of pipe wall section per unit length	(4)
11-20 (F10.0)	PI ($in.^4$/in.)	Moment of inertia of pipe wall section per unit length	
21-30 (F10.0)	PS ($in.^3$/in.)	Section modulus of pipe wall per unit length	

Card 2B. For design only, desired safety factors:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	PFS(1)	Desired safety factor against thrust yielding, Default = 3.0	(5)
11-20 (F10.0)	PFS(2)	Desired safety factor against 20% deflection (20% of diameter), Default = 4.0	
21-30 (F10.0)	PFS(3)	Desired safety factor against elastic buckling, Default = 2.0	

*** GO TO SECTION C ***

Corrugated Steel Commentary

(1) The parameter NONLIN indicates the degree of material nonlinearity to be considered. Most metal culverts experience outer fiber yielding due to bending under normal loading conditions. Consequently, the linear approximation (NONLIN = 0) is questionable except for parameter studies. As a general rule, the bilinear assumption (NONLIN = 2) should be used. However, for Level 1 solutions, the yield-hinge theory (NONLIN = 1) is preferable if more than 50% of the wall section yields. This is because Level 1 uses a smeared average of the bilinear modulus that does not properly represent localized yielding. The yield-hinge theory was developed expressly to treat local yielding (hinging) for Level 1.

(2) For round pipe, PDIA is the pipe diameter measured from wall center to wall center. For elliptical pipe (Level 2), PDIA is the average of the major and minor diameters. For other culvert shapes (Level 3), PDIA is a nominal average diameter; further shape definition is required in Section C.

(3) The bilinear stress-strain model and associated parameters are shown in Figure II-1. The default values provided for the material parameters are recommended for standard corrugated steel culverts.

(4) Only include this card if XMODE = ANALYS. Note, all units are inches.

(5) Only include this card if XMODE = DESIGN. Normal ranges for specified safety factors are:

Thrust yielding, 2.0 - 3.0

Excessive deflection, 3.5 - 4.0

Elastic buckling, 2.0 - 3.0

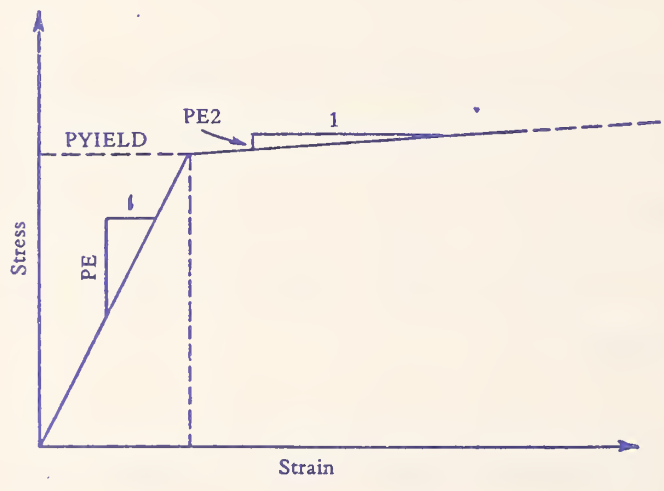


Figure II-1. Bilinear stress-strain parameters for steel.

Corrugated Aluminum Input (Cards 1B, 2B)

Card 1B. Pipe size and material properties:

Columns (format)	Variable (units)	Entry Description	Note
01-05 (I5)	NONLIN	Denotes type of material behavior, = 0, linear stress-strain law = 1, yield-hinge theory = 2, bilinear stress-strain law	(1)
06-15 (F10.0)	PDIA (in.)	Pipe diameter, average	(2)
16-25 (F10.0)	PE (psi)	Elastic Young's modulus of pipe materials, Default = 10.2×10^6 psi	
26-35 (F10.0)	PNU	Poisson's ratio of pipe material, Default = 0.33	
36-45 (F10.0)	PYIELD (psi)	Yield stress of pipe material, Default = 24,000	
46-55 (F10.0)	PELONG (in./in.)	Strain at material rupture, Default = 0.05 in./in.	(3)
56-65 (F10.0)	PDEN (pci)	Density of material for body weight; only applies to Levels 2 and 3, Default = 0.0	
66-76 (F10.0)	PE2 (psi)	Modulus of upper portion of bilinear stress-strain curve; used only with NONLIN = 2, Default = 600,000 psi	

Card 2B. For analysis only, wall properties:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	PA ($in.^2/in.$)	Area of pipe wall section per unit length	(4)
11-20 (F10.0)	PI ($in.^4/in.$)	Moment of inertia of pipe wall section per unit length	
21-30 (F10.0)	PS ($in.^3/in.$)	Section modulus of pipe wall per unit length	

Card 2B. For design only, desired safety factors:

Columns (format)	Variables (units)	Entry Description	Note
01-10 (F10.0)	PFS(1)	Desired safety factor against thrust yielding, Default = 3.0	(5)
11-20 (F10.0)	PFS(2)	Desired safety factor against 20% deflection (20% of diameter), Default = 4.0	
21-30 (F10.0)	PFS(3)	Desired safety factor against elastic buckling, Default = 2.0	
31-40 (F10.0)	PFS(4)	Desired safety factor against strain rupture, Default = 2.0	

*** GO TO SECTION C ***

(1) Recommendations for specifying NONLIN are the same as for corrugated steel (comment 1). In general, use NONLIN = 2.

(2) For round pipe, PDIA is the pipe diameter measured from wall center to wall center. For elliptical pipe (Level 2), PDIA is the average of the major and minor diameters. For other culvert shapes (Level 3), PDIA is a nominal average diameter; further shape definition is required in Section C.

(3) The concern for strain rupture is the primary difference between the treatment of corrugated aluminum and corrugated steel. The ductile range of aluminum terminates in strain rupture. Accordingly, excess bending strain is considered unsafe for aluminum. The bilinear stress-strain parameters are illustrated in Figure II-2 along with the rupture strain parameter. The default values of these parameters are recommended for standard corrugated aluminum pipe.

(4) Only include this card if XMODE = ANALYS. Note, all units are inches.

(5) Only include this card if XMODE = DESIGN. Normal ranges for specified safety factors are:

Thrust yielding, 2.0 - 3.0

Excessive deflection, 3.5 - 4.0

Elastic buckling, 2.0 - 3.0

Outer fiber rupture, 2.0 - 3.0

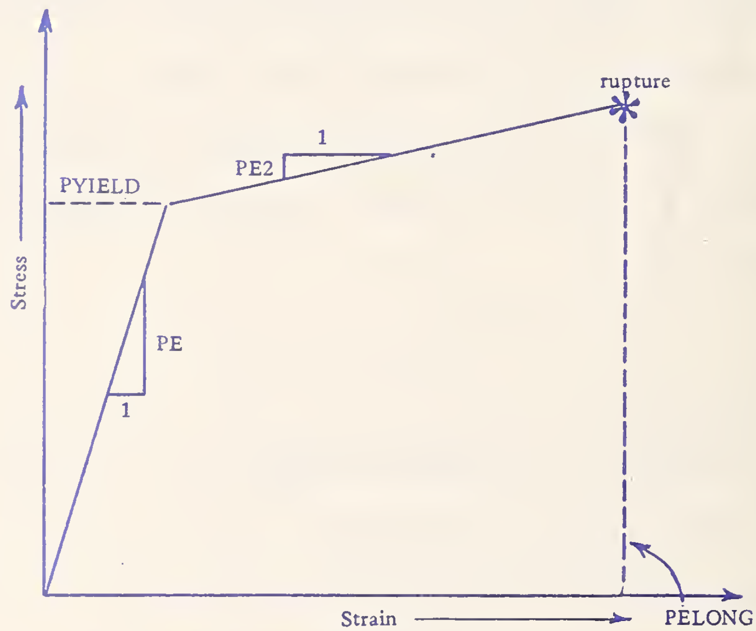


Figure II-2. Bilinear stress-strain parameters for aluminum.

Reinforced Concrete Inpu' ırds 1B, 2B, 3B)

Card 1B. Pipe size, shaı and nonlinear character:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	PDIA (in.)	Inside pipe diameter, average	(1)
11-20 (F10.0)	PT (in.)	Concrete wall thickness, for design this is left blank unless a fixed-wall design is desired	
22-25 (A4)	RSHAPE (word)	Name to select shape of steel cage(s), = CIRC, circular cages, inner and outer = ELLI, elliptical reinforcement, one cage = ARBI, arbitrarily shaped cages, this applies to analysis only, Default = CIRC	(2)
26-30 (I5)	NONLIN	Degree of nonlinearity, = 1, concrete cracking only = 2, also include nonlinear compression of concrete = 3, also include steel yielding, Default = 1	(3)
31-40 (F10.0)	STNMAT(1) in./in.	Concrete strain at which tensile cracking occurs (positive), Default = 0.0 in./in.	(4)
41-50 (F10.0)	STNMAT(2) in./in.	Concrete strain at elastic limit in compression (positive), Default = 1/2 PFPC/PCE (see next card)	
51-60 (F10.0)	STNMAT(3) in./in.	Concrete strain at initial compressive strength, f_c' (positive), Default = 0.002 in./in.	

Card 2B. Concrete and steel properties:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	PFPC (psi)	Compressive strength of concrete, f'_c, Default = 4,000 psi	(5)
11-20 (F10.0)	PCE (psi)	Young's modulus of concrete in elastic range, Default = $33(\text{density})^{3/2}(f'_c)^{1/2}$	
21-30 (F10.0)	PNU	Poisson ratio of concrete, Default = 0.17	
31-40 (F10.0)	PDEN (pcf)	Unit weight of concrete (density), Default = 0.0 for body weight; however, Default = 150 pcf for modulus calculation	
41-50 (F10.0)	PFSY (psi)	Yield stress of reinforcing steel, Default = 40,000 psi	
51-60 (F10.0)	PSE (psi)	Young's modulus of steel Default = 29×10^6 psi	
61-70 (F10.0)	PSNU	Poisson's ratio of steel, Default = 0.3	

Card 3B. For analysis only, steel area and location:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	ASI (in.^{2}/in.)	Area of inner cage reinforcement steel; If RSHAPE = ELLI, this is area of the elliptical case	(6)
11-20 (F10.0)	ASO (in.^{2}/in.)	Area of outer cage reinforcement steel; not used if RSHAPE = ELLI	
21-30 (F10.0)	TBI (in.)	Thickness of concrete cover to center of inner cage, or minimum cover of elliptical cage, Default = 1.25 in.	
31-40 (F10.0)	TBO (in.)	Thickness of concrete cover to center of outer case, not used if RSHAPE = ELLI, Default = 1.25 in.	

Card 3B. For design only, design specifications:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	PFS(1)	Desired safety factor against steel yielding, Default = 1.6	(7)
11-20 (F10.0)	PFS(2)	Desired safety factor against concrete crushing, Default = 2.0	
21-30 (F10.0)	PFS(3)	Desired safety factor against concrete shear failure, Default = 2.0	
31-40 (F10.0)	ALCW (in.)	Allowable maximum crack width for the design load; normally taken as 0.01 in, Default = Crack width is not considered as a design criterion	
48-50 (A3)	GOAL (word)	Code to determine type of wall design, = STD, implies standard wall sizes A, B, and C from ASTM C-76 = OPT, implies continuous wall sizes are assumed for optimum design = FIX, implies fixed wall size is specified and only steel is designed Default = STD	(8)
51-60 (F10.0)	TBI (in.)	Cover to center of steel reinforcement for both inner and outer cages; or, minimum cover of elliptical cage Default = 1.25 in.	
61-70 (F10.0)	SRATIO	Steel area ratio of outer-to-inner cages, only applies to RSHAPE = CIRC, Default = 0.75	

*** GO TO SECTION C ***

(1) For round pipe, PDIA is the pipe diameter measured from inner wall to inner wall. For elliptical pipe (Level 2), PDIA is the average of the major and minor diameters. For other culvert shapes (Level 3), PDIA is a nominal average diameter; further shape definition is required in Section C.

(2) Specification of reinforcement shape by ''RSHAPE'' is relative to the shape of the concrete wall. That is, if RSHAPE = CIRC, two lines of reinforcement, inner and outer, run parallel to the inner and outer pipe wall periphery, regardless of overall pipe shape. If RSHAPE = ELLI, one line of reinforcement traverses the pipe wall from an interior wall position at crown to an exterior wall position at the springline and back to an interior position at the invert. Lastly, if RSHAPE = ARBI, two lines of reinforcement can be specified in any shape relative to the pipe wall. Also, the steel areas may be selectively varied around the pipe; however, this option only applies to the analysis mode.

(3) As a general rule, concrete cracking, nonlinear compression, and steel yielding should be used for all problems (NONLIN = 3). Lesser degrees of nonlinearity are useful for comparative studies. Note, linear modeling with no cracking is achieved by setting NONLIN = 1 and STNMAT(1) = large value.

(4) The nonlinear concrete stress-strain model is defined with measures of strain; i.e., cracking strain STNMAT(1), compressive strain at elastic limit STNMAT(2), and strain at compressive strength STNMAT(3). Figure II-3 illustrates the concrete model and input parameters.

Reinforcing steel is assumed elastic perfectly plastic and does not slip relative to the concrete web (i.e., deformed bars or mesh).

(5) PFPC (i.e., f'_c) and other parameters on this card are supplied with recommended default values for reinforced concrete pipe. Thus, a blank data card may suffice for this input.

(6) Only include this card if XMODE = ANALYS. Definition of the parameters ASI, ASO, TBI, and TBO depend on RSHAPE. For the special case, RSHAPE = ARBI, these parameters are input for each pipe segment or element. Thus, card 3B is repeated ten times for Level 1 or 2 and NPMAT times for Level 3, such that ASI and TBI will define one line of reinforcement; TBI is the distance from the inner wall to the center of steel area ASI. Similarly, ASO and TBO define a second line of reinforcement measured from the outer wall.

For the more common cases, RSHAPE = CIRC or ELLI, card 3B is input once as indicated.

(7) Only include this card if XMODE = DESIGN. Normal ranges of specified safety factors are:

Steel yielding, 1.5 - 2.0

Concrete crushing, 1.5 - 2.0

Shear failure, 2.0 - 3.0

Crack width, 0.01 in.

(8) In the design mode the objective is to determine both concrete wall thickness and required steel area(s) when GOAL = OPT or STD. For the case GOAL = FIX, the specified wall thickness is held constant, and only the steel area is designed. In this case only the crack width and steel yielding criterion are used in the design process.

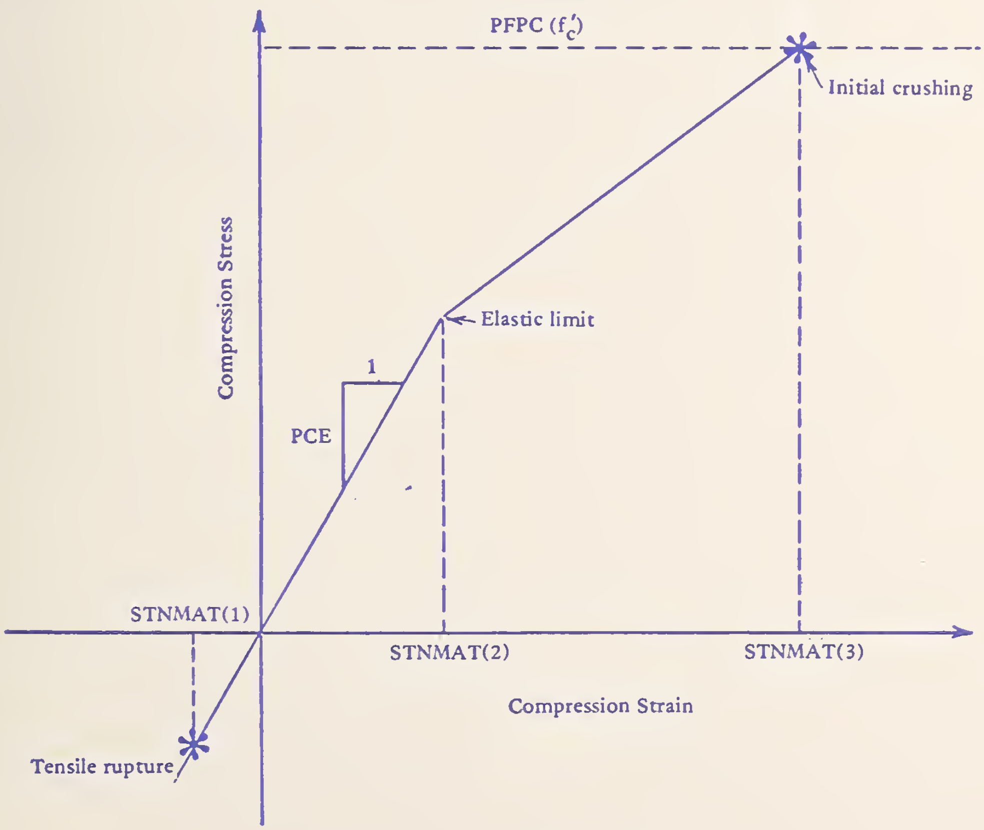


Figure II-3. Concrete stress-strain model.

Plastic Pipe Input (Cards 1B, 2B)

Card 1B. Pipe size and material properties:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	PDIA (in.)	Inside pipe diameter, average	(1)
11-20 (F10.0)	PE (psi)	Young's modulus of pipe material, Default = 1,600,000 psi	
21-30 (F10.0)	PNU	Poisson's ratio of pipe material, Default = 0.35	
31-40 (F10.0)	PULT (psi)	Ultimate material stress at rupture, Default = 25,000 psi	(2)
41-50 (F10.0)	PDEN (pci)	Density of pipe material used for body weight loading; only applies to Levels 2 and 3, Default = 0.0	

Card 2B. For analysis only, plastic pipe wall thickness:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	PT (in.)	Thickness of smooth pipe wall	(3)

Card 2B. For design only, desired safety factors:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	PFS(1)	Desired safety factor against excessive deflection (20% of PDIA), Default = 4.0	
11-20 (F10.0)	PFS(2)	Desired safety factor against outer fiber stress rupture, Default = 3.0	
21-30 (F10.0)	PFS(3)	Desired safety factor against elastic buckling, Default = 3.0	(4)

*** GO TO SECTION C ***

(1) For round pipe, PDIA is the inside diameter. For elliptical pipe (Level 2), PDIA is the average of the major and minor inside diameters. For other culvert shapes (Level 3), PDIA is a nominal average diameter; further shape definition is required in Section C.

(2) The stress-strain law for plastic pipe is assumed linear up to brittle failure at the stress level PULT, as indicated in Figure II-4. The default values for card 2B are representative of plastic reinforced mortar pipe. For other types of brittle plastic the user must supply the appropriate properties. Note, the plastic pipe model is suitable for other brittle materials, such as cast iron or clay pipe.

(3) Only include this card if XMODE = ANALYS. The pipe wall is assumed to be uniform and homogeneous with thickness PT.

(4) Only include this card if XMODE = DESIGN. The normal range of specified safety factors are:

Excessive deflection, 3.0 - 4.0

Outer fiber rupture, 2.5 - 3.5

Elastic buckling, 2.5 - 3.5

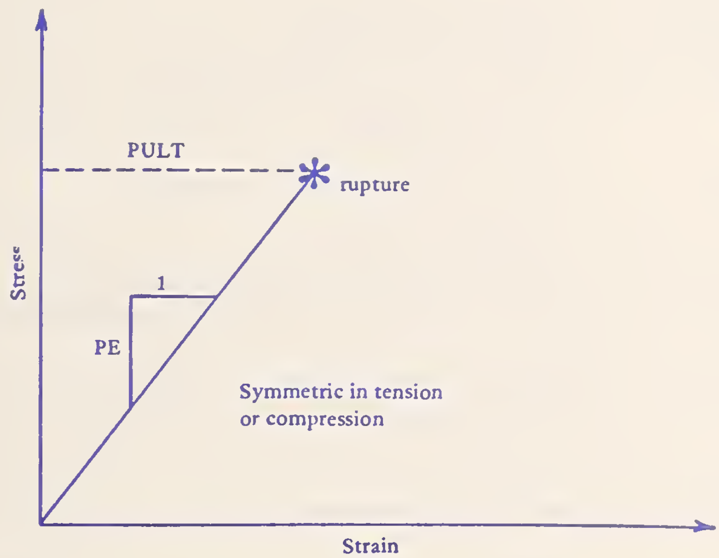


Figure II-4. Stress-strain model for plastic.

Basic Input, (Cards 1B, 2B)

Card 1B. Pipe size:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	PDIA (in.)	Diameter of pipe, average	(1)

Card 2B. Pipe properties (repeat card as necessary):

Columns (format)	Variables (units)	Entry Description	Note
01-05 (I5)	ISEQ1	First pipe element material-sequence number	(2)
06-10 (I5)	ISEQ2	Second pipe element material-sequence number	
11-20 (F10.0)	PE (psi)	Young's modulus of pipe material for the sequence (ISEQ1 to ISEQ2)	(3)
21-30 (F10.0)	PNU	Poisson's ratio of pipe material for the sequence	
31-40 (F10.0)	PA ($in.^2/in.$)	Area of pipe section per unit length for the sequence	
41-50 (F10.0)	PI ($in.^4/in.$)	Moment of inertia of pipe section per unit length for the sequence	
51-60 (F10.0)	PDEN (lb/in.)	Weight of pipe element per unit length for the sequence	

*** GO TO SECTION C ***

Basic Commentary

(1) The basic pipe model allows specification of pipe properties that are nonuniform around the periphery of the culvert, and, thus, is best used with Levels 2 or 3. Only analysis problems can be considered. For round pipes, PDIA is the average diameter from wall center to wall center. For elliptical shapes (Level 2), PDIA is the average of major and minor diameters. For other shapes (Level 3), PDIA is not used; instead, pipe shape is defined in Section C.

(2) For Levels 2 and 3, each pipe element is identified with a separate material number in a consecutive sequence from 1 to NPMAT, traveling clockwise around the pipe (NPMAT = number of pipe elements, NPMAT = 10, for Levels 1 and 2). If consecutive groups of elements have the same material properties, the use of ISEQ1 and ISEQ2 reduces the number of 2B data cards. For example, if all pipe elements have the same properties, then only one card is required with ISEQ1 = 1 and ISEQ2 = NPMAT.

(3) Linear stress-strain models are assumed for all pipe materials described by BASIC. No default material properties are provided, and no safety factor evaluation is determined.

SECTION C - SOLUTION LEVEL DESCRIPTION

Go to subsection corresponding to chosen solution level:

- Level 1
- Level 2
- Level 3

Commentaries are included after the input instructions for each solution level. Note, Level 2 subsection is followed by an additional subsection for ''extended'' Level 2 operations. Extended Level 2 allows for selective modifications of standard Level 2 mesh models.

Level 1 Input (Cards 1C, 2C)

Card 1C. Level 1 system parameters:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	SDEN (pcf)	Density of soil over pipe	(1)
11-15 (I5)	NINC	Total number of load steps or soil lifts, Default = 1	(2)
16-20 (I5)	ISLIP	Code for treatment of pipe-soil interface, = 0, implies no slip, rigid interface bond = 1, implies full slip, frictionless interface	(3)

Card 2C. Level 1 soil parameters (repeat card for each load step, I = 1 to NINC):

Columns (format)	Variables (units)	Entry Description	Note
01-10 (F10.0)	HT(I) (ft)	Soil height above crown at load step I (current total height)	
11-20 (F10.0)	SEH(I) (psi)	Young's modulus of soil in vicinity of pipe at load step I (secant values)	(4)
21-30 (F10.0)	SVH(I)	Poisson's ratio of soil in vicinity of pipe at load step I	

*** END OF INPUT FOR ONE PROBLEM ***

Level 1 Commentary

(1) Level 1 provides a solution for a circular pipe deeply buried in a homogeneous soil. All loading is approximated by an equivalent overburden pressure p_o as indicated in Figure II-5. To simulate gravity loads, Level 1 uses p_o = SDEN [HT(I) - HT(I-1)] for each load step. If it is desired to simulate concentrated loads, the user must artificially increase the soil height HT by an amount ΔH to represent the additional pressure at the pipe crown. Pressure at the crown due to a surface concentrated load Q may be estimated by assuming the load spreads in a 30-degree cone. Therefore, $\Delta H = 3Q/[(\pi)(SDEN)(HT^2)]$. For additional details see Chapter 9 of the engineering manual [1].

In general, gravity loads overshadow contributions from concentrated loads when fill heights exceed 5 feet. When concentrated loads are significant and the cover depth is shallow, Level 2 should be used.

(2) In most design cases it is adequate to place the entire load in one step (NINC = 1). However, if it is desired to study the response history of the pipe, five to ten steps should be used.

(3) Two pipe-soil interface conditions can be considered – slip or no slip. No slip implies both normal and shear forces are transmitted across the interface, whereas slip only transmits normal forces. Generally, no slip is recommended for design problems.

(4) As a rule, the Young's modulus of soil increases for increased states of confining compression. Accordingly, specified values, SEH(I), should correspond to the accumulated overburden pressure, p_o = SDEN*HT(I). Whenever possible specified values should be based on experimental tests of the site soil or other direct sources of information. However, if no information is available, Table II-1 can be used as a guide to estimate SEH(I) as a function of overburden pressure. The table includes three broad soil catagories - granular, mixed, and cohesive with compaction ranging from fair to good. Also shown are estimates for Poisson's ratio and soil density.

If several load steps are specified (NINC > 1), Card 2C is repeated for each step, wherein SEH(I) is the secant modulus for accumulated fill height, HT(I). Level 1 automatically converts the secant values into incremental chord values applicable to the load step. See Chapter 6 of the engineering manual for more discussion on soil models.

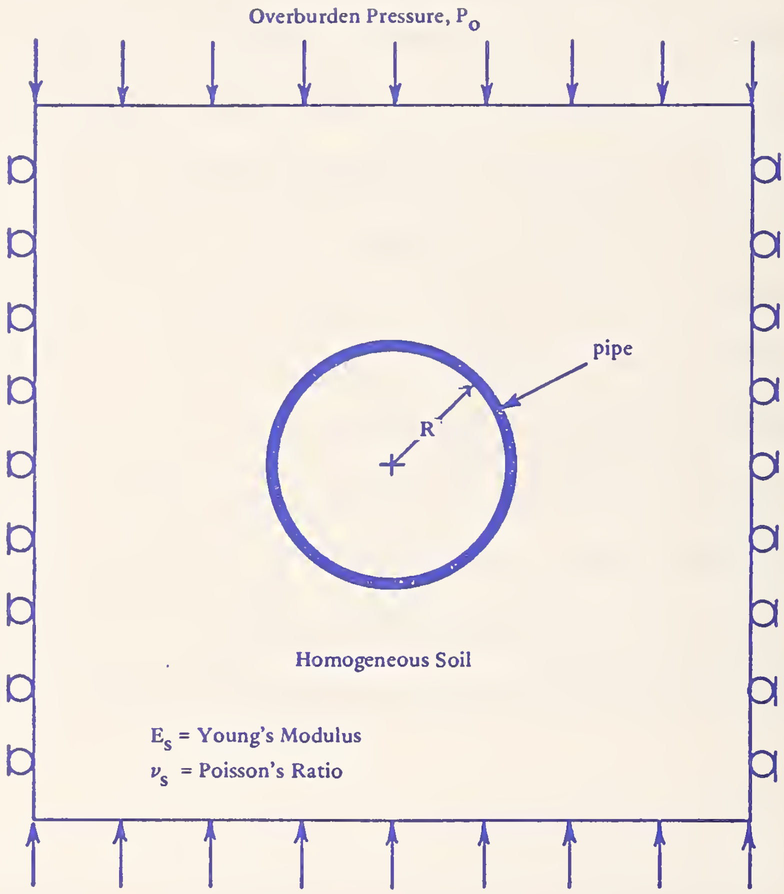


Figure II-5. Approximate model representation of elasticity boundary value problem.

Table II-1. Young's Secant Modulus for a Range of Overburden Pressures and Three Soil Types

Soil	Young's Secant Modulus (psi) for Overburden Pressures of –								Poisson's Ratio	Density (pcf)
	5 psi	10 psi	15 psi	20 psi	25 psi	30 psi	40 psi	50 psi		
Granular										
Fair compaction	550	750	850	1,000	1,100	1,150	1,300	1,400	0.30-0.35	110-150
Good compaction	1,100	1,300	1,500	1,650	1,800	1,900	2,100	2,250		
Mixed										
Fair compaction	400	550	600	700	750	800	900	900	0.30-0.40	100-140
Good compaction	600	850	1,000	1,100	1,200	1,250	1,350	1,450		
Cohesive										
Fair compaction	150	200	225	250	250	250	250	250	0.35-0.40	100-130
Good compaction	250	325	375	375	400	400	400	400		

Level 2 Input (Cards 1C, 2C, 3C, 1D, 2D)

Card 1C. Define mesh type, title, and special options:

Columns (format)	Variable (units)	Entry Description	Note
01-04 (A4)	WORD	Name to identify type of automatic mesh, = EMBA, embankment mesh = TREN, trench mesh = HOMO, homogeneous mesh	(1)
05-72 (17A4)	TITLE	User description of mesh to be printed with output	
73-76 (A4)	WORD1	Command to include frictional pipe-soil interface model, = SLIP, include frictional interface ≠ SLIP, do not include interface	(2)
77-80 (A4)	WORD2	Command to permit user to selectively modify the automatic mesh, = MOD, mesh will be modified ≠ MOD, mesh will not be modified (left justified)	(3)

Card 2C. Define print options and mesh parameters:

Columns (format)	Variable (units)	Entry Description	Note
01-05 (I5)	IPLOT	Signal to create a plot data tape on unit 10, = 0, no data tape created = 1, create data tape	
06-10 (I5)	IWRT	Signal to print out soil responses for all elements, = 0, no soil response printed out = 1, print out soil responses	
11-15 (I5)	MGENPR	Code to control amount of print out of mesh data, = 1, minimal printout; just control data = 2, above, plus node and element input data = 3, above, plus generated mesh data = 4, maximal printout of input data Default = 3	
16-20 (I5)	NINC	Number of construction increments, = -1, combine all lifts into one monolith = 0, used for data check only; all data is read but not executed = N, number of construction increments to be executed, N = 1 to 10	(4)
21-30 (F10.0)	RDIA	Ratio of horizontal to vertical pipe diameter to define elliptical pipe, Default = 1.0 (circle)	
31-40 (F10.0)	HTCOVR (ft)	If WORD = EMBA or HOMO, HTCOVR is total fill soil height above spring-line; if WORD = TREN, HTCOVR is fill soil height above top of trench	(5)
41-50 (F10.0)	DENSTY (pcf)	Density of soil above truncated mesh to be used as equivalent overburden pressure	(6)

continued

Card 2C. continued

Columns (format)	Variable (units)	Entry Description	Note
51-60 (F10.0)	PRESUR (psi)	Uniform surface pressure applied on last construction increment	(7)

Card 3C. Define backpacking or trench geometry:

Columns (format)	Variable (units)	Entry Description	Note
01-05 (I5)	NUMPEL	Code to determine amount of back-packing for embankment mesh only, = 0, no backpacking material; this zone is replaced with fill soil and bedding = N, the number of consecutive elements starting at the crown to be assigned backpacking properties, remaining elements adjacent to pipe are assigned to fill soil zone and bedding, N = 1 to 10	(8)
11-20 (F10.0)	TPAC (in.)	Thickness of backpacking zone around the pipe ($D/16 \leq TPAC \leq 3D/16$, where D is pipe diameter); EMBA only, Default = D/12	
21-30 (F10.0)	TRNDEP (ft)	Depth of trench measured from the pipe invert ($TRNDEP \geq D/4$, where D is the vertical pipe diameter); only required for WORD = TREN	(9)
31-40 (F10.0)	TRNWID (ft)	Width of trench ($1.25D \leq TRNWID < 1.5D$, where D is horizontal pipe diameter); only required for WORD = TREN	

Cards 4C-7C. Cards for modifying Level 2 meshes go here:

If WORD2 = MOD, go to Extended Level 2 for data input instructions; otherwise skip Cards 4C-7C, and complete input with cards 1D and 2D.

Card 1D. Material identifier card (repeat cards 1D and 2D for each material):

Columns (format)	Variable (units)	Entry Description	Note
01-01 (A1)	LIMIT	Last material card-set indicator; = 0, read another set of material definitions = L, this is the last material input	
02-05 (I4)	I	Material identification number; corresponds to the material zone of the chosen mesh type, = 1, for in-situ soil zones or homogeneous mesh = 2, for bedding zones = 3, for embankment fill or trench fill = 4, for embankment backpacking or trench overfill (The above is predefined for Level 2 only.)	(10)
06-10 (I5)	ITYP	Selection of material model to be associated with material zone I, = 1, linear elastic (isotropic) = 2, linear elastic (orthotropic) = 3, (unspecified, to be supplied by user) = 4, overburden dependent = 5, fully nonlinear, Extended-Hardin model = 6, frictional interface model (If WORD 1 = SLIP, see comment)	(11)
11-20 (F10.0)	DEN(I) (pcf)	Density of material I used to compute gravity loads; only applies to ITYP = 1, 2, 3, 4, and 5.	
21-40 (5A4)	MATNAM	User description of material; if ITYP = 1, 2, 3, 4, or 6, MATNAM may be any descriptive information to be printed out with data, for ITYP = 5, MATNAM is used to select the soil classification for the Extended-Hardin model as follows (left justified):	

continued

Card 1D continued

Columns (format)	Variable (units)	Entry Description	Note
21-40 (5A4)	MATNAM	= GRAN, for modeling granular soils = MIXE, for modeling mixed soils = COHE, for modeling cohesive soils = TRIA, for utilizing data from tri-axial tests Default = MIXE	

*** GO TO CARD 2D CORRESPONDING TO ITYP ***

Card 2D. ITYP = 1, linear elastic:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	E (psi)	Young's modulus of material I	(12)
11-20 (F10.0)	GNU	Poisson's ratio of material I	

Card 2D. ITYP = 2, orthotropic, linear elastic:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	CP(1,1) (psi)	Constitutive parameter at matrix position (1,1)	
11-20 (F10.0)	CP(1,2) (psi)	Constitutive parameter at matrix position (1,2)	
21-30 (F10.0)	CP(2,2) (psi)	Constitutive parameter at matrix position (2,2)	
31-40 (F10.0)	CP(3,3) (psi)	Constitutive parameter at matrix position (3,3)	
41-50 (F10.0)	THETA (deg)	Angle of the material axis with respect to the global x-axis	

Card 2D. ITYP = 3, user developed soil model:

Provisions have been made for users to substitute their own soil model in CANDE, in which case data are supplied at this juncture. See system manual.

Card 2D. ITYP = 4, overburden dependent model, user table, (repeat card as needed; last card is blank):

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	H(N) (psi)	Overburden pressure for table entry N	(13)
11-20 (F10.0)	E(N) (psi)	Young's secant modulus for table entry N	
21-30 (F10.0)	GNU(N)	Poisson's ratio for table entry N	

Card 2D. ITYP = 5, and MATNAM = GRAN, MIXE, or COHE; Extended-Hardin model for three soil classifications:

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	XNUMIN	Poisson's ratio at low shear strain, Default = 0.10	(14)
11-20 (F10.0)	XNUMAX	Poisson's ratio at high shear strain, Default = 0.49	
21-30 (F10.0)	XQ	Shape parameter q for Poisson's ratio function, Default = 0.26	
31-40 (F10.0)	VOIDR	Void ratio of soil, range 0.1 to 3.0; see comments for default	
41-50 (F10.0)	SAT	Ratio of saturation, range 0.0 to 1.0; see comments for default	
51-60 (F10.0)	PI	Plasticity-index/100, range 0.0 to 1.0; see comments for defaults	
61-65 (I5)	NON	Maximum iterations per load step, Default = 5	

Card 2D. ITYP = 5, and MATNAM = TRIA; Extended-Hardin model for triaxial data input

Columns (format)	Variable (units)	Entry Description	Note
01-30 (3F10.0)	------	Same as card above (XNUMIN, XNUMAX, XQ)	
31-40 (F10.0)	S1	Hardin parameter used to calculate maximum shear modulus	
41-50 (F10.0)	C1	Hardin parameter used to calculate reference	
51-60 (F10.0)	A	Hardin parameter used to calculate hyperbolic shear strain	
61-65 (I5)	NON	Maximum iterations per load step, Default = 5	

Card 2D ITYP = 6, interface property definition (must be defined with Card 1D ten times if WORD 1 = SLIP):

Columns (format)	Variable (units)	Entry Description	Note
01-10 (F10.0)	ANGLE (deg)	Angle from x-axis to normal of interface at the nodel point (direction of normal is IX(1) to IX(2); see comment)	(15)
11-20 (F10.0)	FCOEF	Coefficient of friction between pipe and soil at interface nodal point	
21-30 (F10.0)	TENSIL (lb)	Tensile breaking force at contact point, Default = 0.0	

*** INPUT COMPLETED FOR ONE PROBLEM ***

Level 2 Commentary

(1) Level 2 allows the selection of three fundamental culvert installation models; the embankment mesh (Figure II-6), the trench mesh (Figure II-7), and the homogeneous mesh, where all soil zones have the same material properties; the construction increments are as in the embankment mesh. Level 2 is restricted to installations symmetric about the vertical centerline of the pipe. Accordingly, only half the system is modeled with finite elements. The automatic generation defines all nodes, elements, construction increments, material zones, and boundary conditions. The basic mesh topology contains 86 quadrilateral elements for the soil zones and ten pipe elements (see Extended Level 2 for mesh topology). By selectively identifying each element with a material zone number and a construction sequence number, the embankment mesh and trench mesh are automatically constructed from the same mesh pattern.

(2) If WORD1 = SLIP, the mesh is automatically altered to include eleven interface elements at common nodes between pipe and soil. The interface model allows for frictional sliding, complete separation, and rebonding of the pipe-soil interface during the loading schedule. This option should be restricted to special problems.

(3) If it is desired to alter the standard Level 2 configurations, set WORD2 = MOD. In so doing, the user must supply additional data

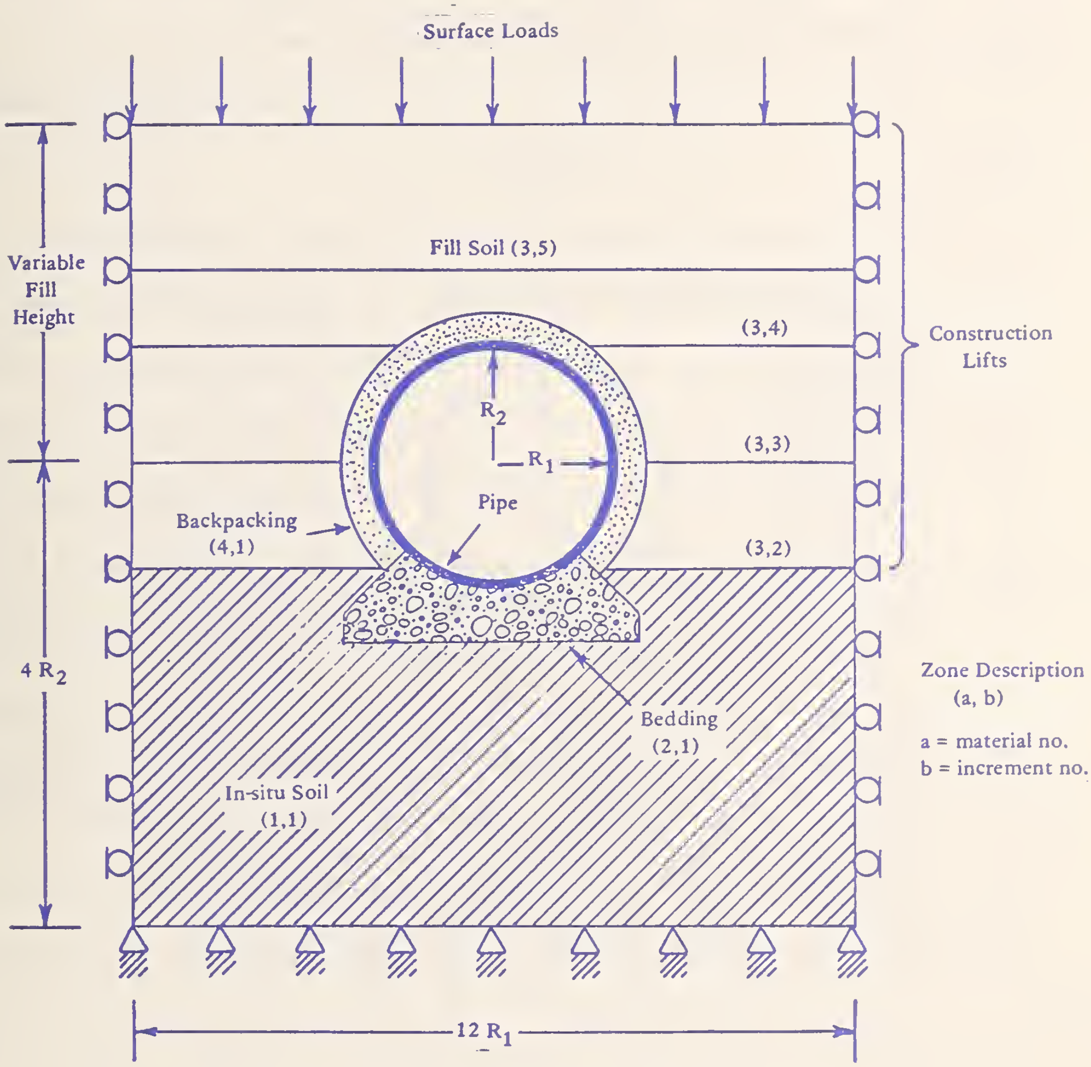


Figure II-6. Embankment model of Level 2 boundary value problem.

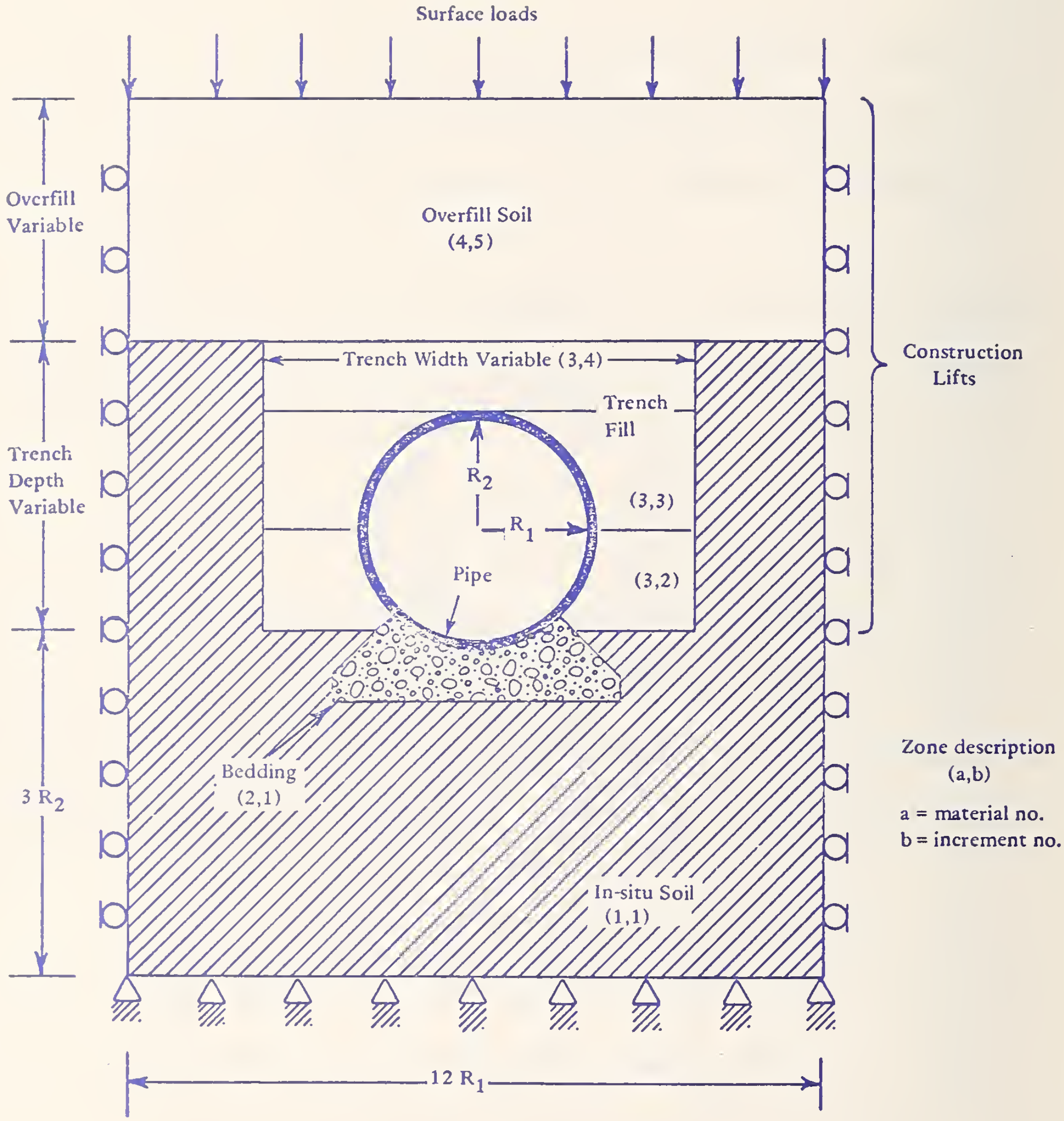


Figure II-7. Trench model of Level 2 boundary value problem.

cards C4 through C7 when indicated. Some motivations for altering the standard Level 2 mesh are: applying concentrated loads, changing bedding shape, incorporating an imperfect trench, modifying culvert shapes, etc. It is wise to exercise standard Level 2 options before using the Extended Level 2 option.

(4) A maximum number of ten construction increments may be used to simulate the construction process of placing soil in layers. The first increment is the in-situ soil, bedding, and pipe; second, fill soil up to the springline; third, fill from springline to crown; fourth, fill from crown to 1.25 diameter above springline; and fifth, fill up to a maximum of 2 diameters above springline. Thereafter, equivalent overburden pressure is used if required.

(5) For the embankment or homogeneous mesh, HTCOVR (see Figure II-6) specifies the total fill height above the springline, which must be at least 0.75 diameter. If HTCOVR is less than 2 diameters, the mesh surface coincides with HTCOVR. On the other hand, if HTCOVR is greater than 2 diameters, the mesh surface will be truncated at 2 diameters above the springline, and the remaining soil weight will be automatically applied to the mesh surface in equal increments of overburden pressure for the remaining construction increments.

For the trench mesh (see Figure II-7), HTCOVR specifies the additional height of overfill above the top of the trench, if any. If the combined

trench fill and overfill height is above 2 diameters from the springline, the mesh will be truncated at 2 diameters, and the remaining soil weight will be applied in equal increments of overburden pressure.

(6) When the mesh surface is truncated at 2 diameters above the springline, the user must specify the soil density of the remaining soil above the mesh surface to be used in computing the additional overburden pressure; i.e., p_o = density (soil height - mesh height).

(7) To mimic Level 1 or to approximate deep fill situations, surface pressure loads, PRESUR, can be used in place of gravity loads. In such cases, set NINC = -1, DENSTY = 0.0, and determine PRESUR as the product of fill height above crown times soil density.

(8) The automated backpacking feature is only applicable to the embankment mesh (see Figure II-6). (For the trench mesh, Extended Level 2 can be used to define backpacking.) There are ten candidate backpacking elements immediately adjacent to the ten pipe elements. The variable NUMPEL specifies how many consecutive elements starting at the crown are assigned backpacking properties. For example, if NUMPEL = 5, backpacking covers the top half of the pipe; if NUMPEL = 10, the entire pipe is surrounded with a backpacking ring, including part of the bedding zone.

(9) The trench depth (TRNDEP) is automatically scaled up to the nearest quarter diameter depth. For example, if the trench depth is specified between 1.0 and 1.25 diameters, the trench depth is set at 1.25 diameters. For trench depths greater than 1.25 diameters, the mesh surface coincides with the top of the trench, and any overfill soil (material zone 4) is treated as equivalent overburden pressure. To avoid ''skinny'' elements, do not use trench depths in the range 1.25 to 1.30 diameters.

(10) The user is free to assign any material stress-strain model, ITYP = 1, 2, 3, 4, or 5, to each material zone I. The material zone numbers correspond to predefined areas of the Level 2 mesh. For the homogeneous mesh (WORD = HOMO), the entire mesh is zoned with I = 1. For the embankment mesh, the zones are: in-situ soil (I = 1), bedding (I = 2), fill soil (I = 3), and backpacking (I = 4). Backpacking only needs to be specified if NUMPEL = 0. Lastly, for the trench mesh, the zones are: in-situ soil (I = 1), bedding (I = 2), trench fill (I = 3), and trench overfill (I = 4).

(11) The selection of the material stress-strain model, ITYP, depends on the desired characteristics of material behavior. A full discussion of each model is given in the engineering manual. Naturally, the model selected should be commensurate with experimental information of the material behavior. If information is scanty, the linear model, ITYP = 1, will provide reasonable results. A more realistic model for

soils is provided with overburden dependent model, ITYP = 4; it is recommended for general use. When a complete set of triaxial soil data is available, the fully nonlinear model, ITYP = 5, provides the most realistic soil model. Provision has been made for the user to incorporate his own soil model subroutine in CANDE under the heading ITYP = 3.

Lastly, the interface model, ITYP = 6, is only associated with interface elements and, for Level 2 operations, needs only to be input when WORD1 = SLIP. In such cases, every interface element with a different normal angle is identified with a different material indicator, I (see comment 15).

(12) The linear elastic model implies the soil zone is assigned constant values for Young's modulus and Poisson's ratio. See Table II-1 for typical soil properties.

(13) For the overburden dependent model, Card 2D is repeated two to ten times, thereby constructing a table of material properties versus overburden pressure for material zone I. (The last card is blank to terminate reading.) Once the table is established, CANDE computes the overburden pressure for each element in zone I by adding the vertical stress from the previous load step to one-half of the current increment of body weight stress above each element. Using this value of overburden pressure, the material properties are linearly interpolated from the input table to be used in the current solution step. Material properties are assumed constant beyond the end points of the table.

Typical overburden dependent soil properties are given in Table II-1 and can be used if no other data are available.

(14) The Extended-Hardin soil model employs a variable shear modulus and a variable Poisson's ratio. The user should consult Chapter 6 of the engineering manual before implementing this model. The model is best used in conjunction with a set of triaxial data (MATNAM = TRIA); however, the model can be defined without triaxial tests by specifying the soil classification (MATNAM = GRAN, MIXE, or COHE), along with the void ratio, percent saturation, and plasticity index.

Default values for these quantities are:

	GRAN	MIXE	COHE
Void ratio	0.60	0.50	1.00
Percent saturation/100	0.00	0.50	0.90
Plasticity index/100	0.00	0.05	0.20

(15) In the case of Level 2 with WORD1 = SLIP, the material properties for the interface elements are different for each element because the interface normal, ANGLE, changes around the pipe periphery. Therefore, Cards 1D and 2D must be input for each of the eleven interface elements, starting with I = 1 at the pipe invert counterclockwise to I = 11 at the crown. If the pipe is circular, the respective ANGLE for the element normals are: -90, -72, -54, -36, -18, 0, 18, 36, 54, 72, and 90 degrees.

If the interface shear force exceeds the product of the normal force and the friction coefficient (FCOEF), the interface element permits relative movement according to the Coulomb friction hypothesis. Should the interface normal force exceed the tensile breaking limit (TENSIL), the contact surfaces will separate from each other and only rebond if subsequent loading brings the interface back together. Note, in Level 3 operations, interfaces between two soil bodies can be defined as well as interfaces between pipe and soil.

Extended Level 2 Input (Cards 4C, 5C, 6C, and 7C)

Card 4C. Number of quantities to be modified:

Columns (format)	Variable (units)	Entry Description	Note
01-05 (I5)	NEWXY	Number of nodal points to be changed with card 5C	(1)
06-10 (I5)	NEWEL	Number of element definition cards to be changed with Card 6C	
11-15 (I5)	NEWBD	Number of new boundary conditions that will be defined with Card 7C, note, this number is restricted to less than 50 due to storage requirements	

Card 5C. Redefine nodal coordinates. (Repeat this card NEWXY times; skip this card if NEWXY = 0):

Columns (format)	Variable (units)	Entry Description	Note
01-05 (I5)	NEWNP	Number of nodal points whose coordinates are to be changed	(2)
11-20 (F10.0)	XCOORD (in.)	New x-coordinate location of NEWNP	
21-30 (F10.0)	YCOORD (in.)	New y-coordinate location of NEWNP	

Card 6C. Redefines element parameters (repeat NEWEL times; skip if NEWEL = 0):

Columns (format)	Variable (units)	Entry Description	Note
1-5 (I5)	NE	Element number whose parameters are to be changed	(3)
6-10 (I5)	NP(1)	New node number I of element connectivity; leave blank if no change	
11-15 (I5)	NP(2)	New node number J of element connectivity; leave blank if no change	
16-20 (I5)	NP(3)	New node number K of element connectivity; leave blank if no change	
21-25 (I5)	NP(4)	New node number L of element connectivity; leave blank if no change	
26-30 (I5)	NP(5)	New material identification number; leave blank if no change	
31-35 (I5)	NP(6)	New construction increment number; leave blank if no change	
36-40 (I5)	NP(7)	Leave this entry blank unless the interface elements are to be altered	

Card 7C. Define additional boundary conditions (Repeat this card NEWBD times; if NEWBD = 0, skip this card):

Columns (format)	Variable (units)	Entry Description	Note
01-05 (I5)	NU	Nodal point number where additional boundary condition is specified	(4)
06-10 (I5)	IFLAG(1)	Boundary condition code for x-coordinate: = 0, force boundary condition (load) = 1, displacement boundary condition	
11-20 (F10.0)	BV(1) (lb/in. or in.)	Applied x-force load (lb/in.) or x-displacement (in.), depending on value of IFLAG(1)	
21-25 (I5)	IFLAG(2)	Boundary condition code for y-coordinate: = 0, force boundary condition (load) = 1, displacement boundary condition	
26-35 (F10.0)	BV(2) (lb/in. or in.)	Applied y-force load (lb/in.), or y-displacement (in.), depending on value of IFLAG(2)	
36-45 (F10.0)	BY(3) (deg)	Angle for skew boundary conditions; angle is measured counterclockwise from the global x-axis	
46-50 (I5)	IA	Construction increment in which boundary condition is activated; force boundary conditions are applied only during increment IA, Default = 1.0	

*** RETURN TO SECTION C FOR CARDS 1D AND 2D ***

Extended Level 2 Commentary

(1) Extended Level 2 permits the user to adjust the standard Level 2 finite element mesh data to redefine nodal coordinates, to add or alter material zones, to change the construction sequence numbering, and to add concentrated loads or other boundary conditions.

To utilize Extended Level 2 effectively, it is necessary to know the mesh configurations. The nodal point and element numbering scheme is the same for all meshes, except when interface elements are included (WORD1 = SLIP); in this case the basic numbering scheme is altered to accommodate the 22 extra nodes required by the 11 interface elements. Figures II-8 and II-9 illustrate the basic element and node numbering schemes. The alteration of the basic node numbering scheme to include interface elements is identified in Table II-2.

For either configuration, the nodal coordinates, material zones, construction increment numbering, and loading depend on the parameters specified on Cards 1C through 3C. Consequently, the user should obtain mesh data output from standard Level 2 to serve as reference for Extended Level 2.

(2) New coordinates can be specified for any and all existing nodes; see Figure II-9 for reference. Note automatic mesh checking routines are by-passed in Extended Level 2 operations; therefore, extreme care must be taken to avoid defining nodal coordinates that result in ''badly shaped'' or ''inside-out'' elements.

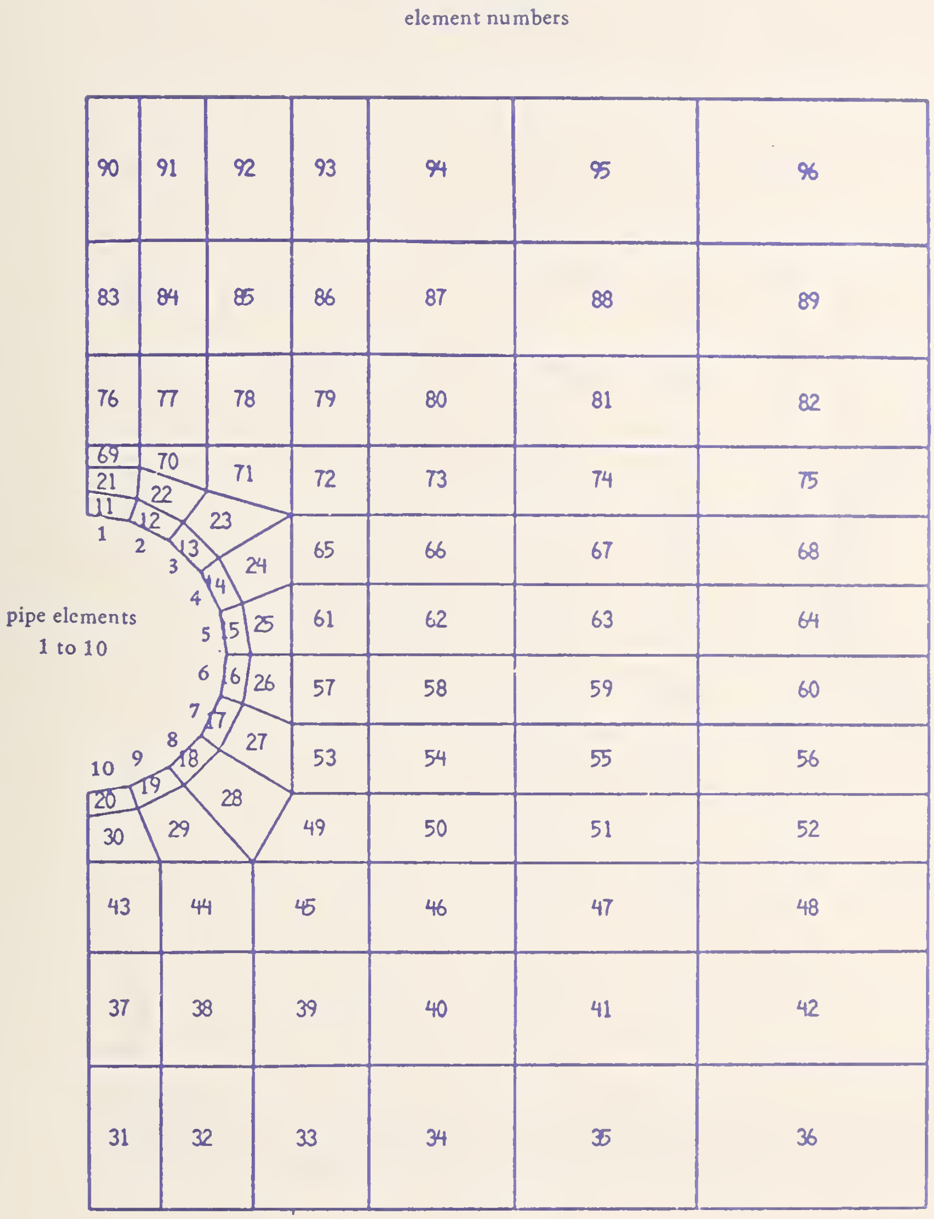


Figure II-8. Basic element numbering scheme.

nodal point numbers

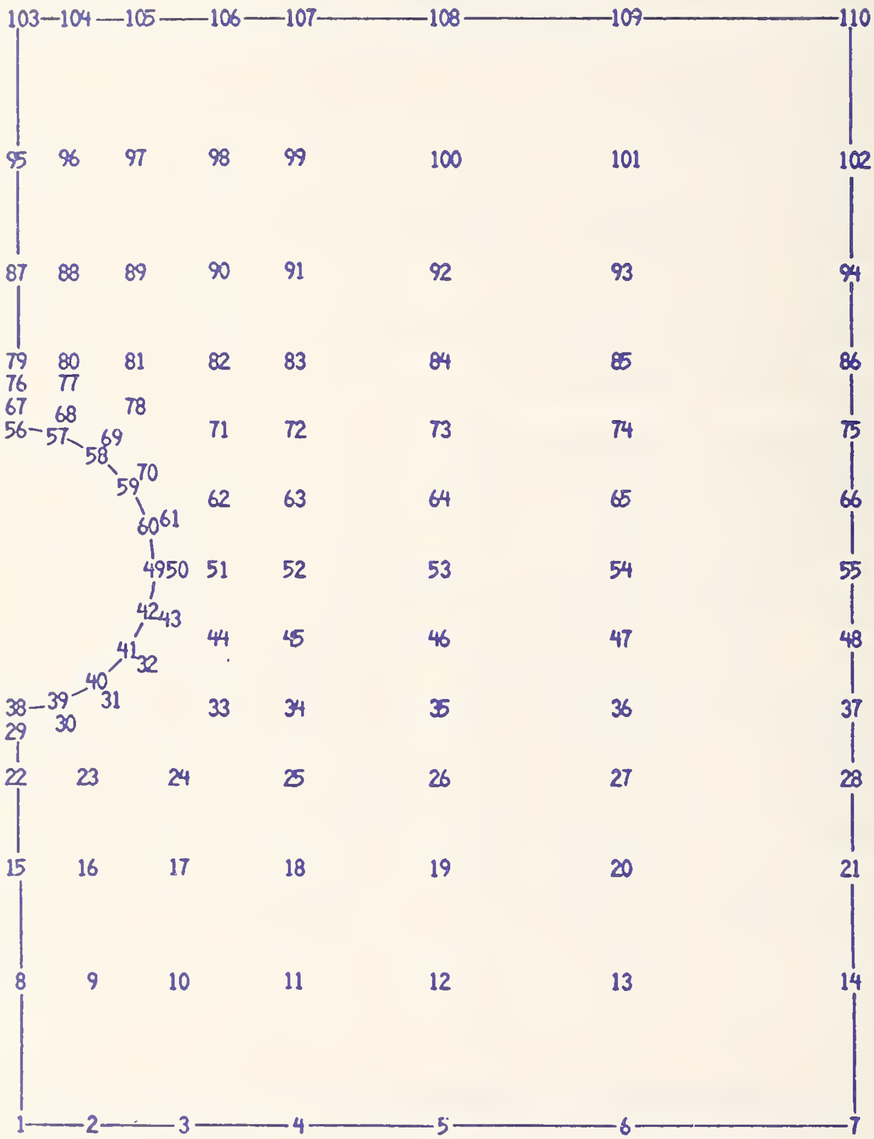


Figure II-9. Basic node numbering scheme.

Table II-2. Corresponding Node Table for WORD1 = SLIP

Basic Scheme Node	Slipping Scheme Node(s)[a]	Basic Scheme Node	Slipping Scheme Node(s)[a]
1	1	50	62
2	2	51	63
.	.	.	.
.	.	.	.
37	37	55	67
38	38, 39, 40	56	68, 69, 70
39	41, 42, 43	57	71, 72, 73
40	44, 45, 46	58	74, 75, 76
41	47, 48, 49	59	77, 78, 79
42	50, 51, 52	60	80, 81, 82
43	53	61	83
44	54	62	84
.	.	.	.
.	.	.	.
48	58	.	.
49	59, 60, 61	110	132

[a]Instead of one node at the pipe-soil interface locations, three nodes are defined at the same location to form the interface element. For every node triplet above (a, b, c):

a = pipe node IX(1)

b = soil node IX(2)

c = ‘‘free node’’ IX(3)

Note: The eleven interface elements are numbered 97 through 107, beginning at the invert and continuing counterclockwise to the crown.

(3) New element properties can be defined for any and all existing elements; see Figure II-8 for reference. The element connectivity array, NP(1), NP(2), NP(3), and NP(4), contains the nodes connected to each element in counterclockwise order. Generally, there will be little motivation to change the connectivity. However, the material identification number, NP(5), and the construction increment number, NP(6), allow selective changes to material zoning. For example, bedding zones can be expanded by assigning those elements in the expanded bedding zone NP(5) = 2 and NP(6) = 1. Further, new material zones, such as an imperfect trench zone (e.g., NP(5) = 5), can replace existing zones as desired. If it is desired to set any NP(I) value to zero, enter NP(I) = -1.

(4) The standard Level 2 options are limited to gravity loads and uniform surface pressure loads. A prime purpose of Extended Level 2 is to permit consideration of concentrated strip loading, which is inherent for plane strain, by assigning to it any node (or nodes) desired. It must be remembered that Level 2 employs symmetry; therefore, any assigned load is automatically applied symmetrically. As an example, to apply a concentrated strip load, q = 1,000 lb/in., on the soil surface directly over the pipe crown, set NU = 103 (basic mesh) and BV(2) = -500.0 (i.e., -q/2); all other entries are zero (or blank), except for IA, which defines the desired load increment number.

To represent a single concentrated point load, Q, by a strip load, q, let q = 3Q/4L, where L is the shortest distance from the point load to the pipe crown. This approximation is based on equating vertical

stresses (at the pipe crown) between free field theories for concentrated and strip loadings.

Level 3 Input (Cards 1C, 2C, 3C, 4C, 5C, 1D, 2D)

Card 1C. Mesh identification card:

Columns (format)	Variable (units)	Entry Description	Note
01-04 (A4)	WORD (word)	Word to denote user-defined mesh is forthcoming, = PREP, Level 3 data are read ≠ PREP, error	(1)
06-73 (17A4)	TITLE (words)	User description of the mesh to be printed with output	

Card 2C. Control parameters for Level 3 solution:

Columns (format)	Variable (units)	Entry Description	Note
01-05 (I5)	NINC	Number of construction increments; limits of NINC are 1 to 10, Default = 1	(2)
06-10 (I5)	MGENPR	Control for amount of printout of mesh data, = 1, minimal printout; just control data = 2, above, plus node and element input data = 3, above, plus generated input data = 4, maximal output of mesh data Default = 3	
11-15 (I5)	NPUTCK	Determines if execution or data check: = 0, execute data = 1, check data only, terminate	
16-20 (I5)	IPLOT	If a nonzero value is entered, the plotting file, unit 10, will contain the input mesh data and structural responses for each load step	
21-25 (I5)	IWRT	If a nonzero value is entered, the interface and continuum element responses will be printed out	
26-30 (I5)	NPT	Total number of nodal points in the mesh	
31-35 (I5)	NELEM	Total number of elements in the mesh	
36-40 (I5)	NBPTC	Number of boundary conditions for this problem	

Card 3C. Nodal point definition, basic generation (repeat as needed):

Columns (format)	Variable (units)	Entry Description	Note
01-01 (A1)	LIMIT (letter)	Signal to indicate the last node input, ≠ L, more nodal cards to come = L, this is last nodal card	
02-05 (I4)	NNP	Nodal point number; must be between 1 and NPT	
10-10 (I1)	MODEG	Defines generation mode between previous card and this card, = 0, standard input, no generation = 2, generates nodes between previous card and current card in the manner requested below	(3)
11-20 (F10.0)	XCOORD (in.)	x-coordinate of NNP	
21-30 (F10.0)	YCOORD (in.)	y-coordinate of NNP	
31-35 (I5)	NPINC	Increment to be added to each generated node, if MODEG = 2 (positive), Default = 1	(4)
41-50 (F10.0)	SPACNG	Ratio of distance between successively generated pairs of nodes, if MODEG = 2; only applies to straight line generation; Default = 1.0	(5)
51-60 (F10.0)	RADIUS (in.)	Defines radius of generated curve, if MODEG = 2, = 0.0, straight line generation ≠ 0.0, circular arc generation; convexity to the right in traveling from previous node to current node	(6)

Card 3C. Nodal point definition, advanced generation (repeat as needed):

Columns (format)	Variable (units)	Entry Description	Note
01-01 (A1)	LIMIT (letter)	Last nodal card indicator ≠ L, implies there are more nodal cards = L, implies this is the last nodal card	
02-05 (I4)	NNP	Nodal point number must be between 1 and NPT	
06-08 (I3)	KRELAD	Permits defining the coordinates of the node NNP by referring to previously defined nodes (associated with MODEG = 0, or 2), = 0, no reference to another node = 1, x-coordinate will be specified by a previously defined node = 2, y-coordinate will be specified by a previously defined node = 3, both coordinates will be specified by previously defined nodes	(7)
09-09 (I1)	LGTYPE	Allows for Laplace generation in one coordinate direction only; or generation along a quarter of an ellipse, = 0, no action = 1, x-coordinate of the generated node will be Laplace-generated = 2, y-coordinate of the generated node will be Laplace-generated = 4, one quarter of an ellipse will be generated	(8)

Columns (format)	Variable (units)	Entry Description	Note
10-10 (I1)	MODEG	Defines generation mode between previous card and this card, = 0, standard input, no generation = 1, no generation; recalls coordinates of a previously defined node = 2, generates nodes between previous card and this card = 3, generates nodes between previous card and this card, where the nodal point NNP on this card has been previously defined = 5, nonsequential node number input; allows for the generation of geometric lines without the need for incremental node numbering	(9)
11-20 (F10.0)	XCOORD (in. or node)	Defines the x-coordinate of NNP, = x-coordinate value, if KRELAD = 0,2 = a node number if KRELAD = 1 or 3 (right justified)	
21-30 (F10.0)	YCOORD (in. or node)	Defines the y-coordinate of NNP, = y-coordinate value, if KRELAD = 0 or 1 = a node number, if KRELAD = 2 or 3 (right justified)	
31-35 (I5)	NPINC	Increment to be added to each generated node, if MODEG = 2 or 3, Default = 1.0	
41-50 (F10.0)	SPACNG	Ratio of distance between successively generated pairs of nodes, if MODEG = 2 or 3; only applies to straight line generation, Default = 1.0	
51-60 (F10.0)	RADIUS	Defines radius of generated curve, = 0.0, straight line generation ≠ 0, circular arc generation; convexity to the right in traveling from previous node to current node	

Card 4C. Element definition card:

Columns (format)	Variable (unit)	Entry and Description	Note
01-01 (A1)	LIMIT (letter)	Last element card indicator, ≠ L, implies there are more element cards = L, implies this is last element card	
02-05 (I4)	NE	Element number; must be between 1 and NELEM	(10)
06-10 (I5)	IX(1)	Node number I of element connectivity	
11-15 (I5)	IX(2)	Node number J of element connectivity	
16-20 (I5)	IX(3)	Node number K of element connectivity, = K, node for quad and triangular elements = 0, for beam elements = A node unused by any other element for interface elements	
21-25 (I5)	IX(4)	Node number L of element connectivity, = L, node for quad elements = 0, for beam, triangular, and interface elements	
26-30 (I5)	IX(5)	Material identification number, = 1 to 10, for quad and triangular elements = 1 to 30, for beam elements = 1 to 30, for interface elements	(11)
31-35 (I5)	IX(6)	Construction increment number in which element enters system, Default = 1	
36-40 (I5)	IX(7)	Set to 1 to designate an interface element otherwise leave blank	
41-45 (I5)	INTRAL	Node increment to be added to connectivity nodes for element row generation, Default = 1	(12)

continued

Card 4C. continued

Columns (format)	Variable (units)	Entry Description	Note
46-50 (I5)	NUMLAY	Number of element rows to be generated, Default = 1	(13)
51-55 (I5)	INTERL	Node number increment between element rows	

Card 5C. Boundary conditions:

Columns (format)	Variable (units)	Entry Description	Note
01-01 (A1)	LIMIT	Last boundary condition indicator, ≠ L, implies there are more boundary condition cards = L, implies this is last boundary condition card	
02-05 (I4)	NP	Nodal point number for boundary condition	(14)
06-10 (I5)	IIFLG(1)	Boundary code for x-coordinate, = 0, force boundary condition = 1, displacement boundary condition	
11-20 (F10.0)	BIVD(1)	Value of boundary condition in x direction, = applied force, if IIFLG(1) = 0 = displacement, if IIFLG(1) = 1	
21-25 (I5)	IIFLG(2)	Boundary code for y-coordinate = 0, force boundary condition = 1, displacement boundary condition	
26-35 (F10.0)	BIVD(2) (lb/in.)	Value of boundary condition in y direction, = applied force, if IIFLG(2) = 0 = displacement, if IIFLG(2) = 1	
36-45 (F10.0)	THETA (deg)	Angle for skewed boundary condition; measured counterclockwise from x-axis	(15)
46-50 (I5)	IA	Construction increment in which this boundary condition is activated; force boundary conditions are only applied during this increment, Default = 1	
51-55 (I5)	NNP	Final node number in a sequence of boundary conditions to be generated	(16)

continued

Card 5C. continued

Columns (format)	Variable (units)	Entry Description	Note
56-60 (I5)	INCR	Node number increment used to generate boundary condition nodes NP to NPP	
61-70 (F10.0)	PJ (psi)	Pressure magnitude at the first node of the sequence, NP	(17)
71-80 (F10.0)	PK (psi)	Pressure magnitude at the last node in the sequence, NNP	

Card 1D. Material identifier card:

Follow instructions for Card 1D of Level 2 input section. The only difference is that the material number, I, corresponds to the user's material zone scheme, IX(5), and not the Level 2 material zoning scheme.

Card 2D. Material parameters (depends on ITYP):

Follow instructions for Card 2D of Level 2 input section with the corresponding ITYP.

*** INPUT COMPLETED FOR ONE PROBLEM ***

Level 3 Commentary

(1) Level 3 is the customary method of finite element input. Accordingly, the user must prepare finite element mesh data representative of the soil-culvert system to be designed or analyzed. In so doing, four groups of data cards must be completed for Level 3 in addition to the Control Cards 1C and 2C. These cards are: (1) nodal point definition (Cards 3C basic or advanced), (2) element definition (Cards 4C), (3) boundary conditions (Cards 5C), and (4) material property definition (Cards 1D and 2D, same as Level 2).

To aid the user, CANDE is equipped with many sophisticated mesh generation features that can greatly reduce the amount of input data. These features are discussed as they arise in the input instructions.

(2) The number of construction increments, NINC, dictates how many load steps CANDE will process. All elements with construction increment numbers less than or equal to the current load step are included in the current stiffness matrix.

(3) The nodal point definition, Card 3C, is given with two versions to provide an option of ''basic'' or ''advanced'' node generation schemes. Actually, the basic option is a subset of the advanced option, but is given separately to minimize confusion. The basic option provides node generation features commonly employed in most finite element programs

and is relatively straightforward. On the other hand, the advanced option is more powerful but requires some ‘‘learning’’ on the part of the user.

For the basic option, when MODEG = 0, the input node NNP is assigned the coordinates XCOORD and YCOORD and other entries are ignored. When MODEG = 2, nodes are generated beginning from the node number defined on the previous card to the node number NNP defined on the current card.

(4) The generated nodes are numbered by successively adding NPINC to the previous node number until the sum is greater or equal to NNP. The last node is always numbered NNP. Accordingly, the number of nodal points generated is (NNP - NNP*)/NPINC, where NNP* is the node number on the previous card. Node generation can go in reverse, i.e., NNP* can be greater than NNP, but NPINC is input positive. Nodes can be input in any order.

(5) The coordinates assigned to generated nodes between NNP* and NNP depend on SPACNG for straight lines and RADIUS for circular areas. If SPACNG = 1.0, all generated nodes will be evenly spaced. If SPACNG > 1.0, the lengths between successively generated nodes will grow with the ratio SPACNG. Similarly, if SPACNG < 1.0, successive lengths will shrink by the ratio SPACNG.

(6) To generate nodes in a circular arc, specify the arc radius. All arc segments are uniformly spaced, and the arc generation must be less or equal to 180 degrees. If RADIUS is specified positive, the convexity of the arc is to the right in traveling from NNP* to NNP. Opposite curvature is given for a negative radius.

(7) The advanced node generation scheme presents the additional parameters KRELAD, LGTYPE, and extensions to MODEG. Other entries are the same as the basic generation scheme.

The parameter KRELAD allows one to specify the x- and/or y-coordinates of the current node by referring to coordinates of nodes previously defined. Thus, when KRELAD $\neq 0$, the variables XCOORD and/or YCOORD are assigned the reference nodal numbers instead of coordinate values. KRELAD is only used on cards with MODEG = 0 or 2.

(8) The parameter LGTYPE is used for two distinct node generation commands. For the case LGTYPE = 1 or 2, the command is for one-coordinate Laplace generation, whereas for the case LGTYPE = 4, the command is for generation of one-quarter of an ellipse. In the first case, one-coordinate Laplace generation is only valid for straight line generation with MODEG = 2. If LGTYPE = 1, the y-coordinate is specified by the straight line generation, but the x-coordinate is set by the Laplace averaging scheme, and vice versa if LGTYPE = 2.

The ellipse command can be used with MODEG = 2 or 3; it generates one-fourth of an ellipse between the node NNP* defined on the previous card and the node NNP on the current card. The elliptical quadrant is generated counterclockwise with convexity on the right when traveling from NNP* to NNP.

(9) In addition to MODEG = 0 and 2 defined in the ''basic'' scheme, MODEG = 1 allows one to recall the coordinates of any previously defined node, NNP. The motivation for this is to provide a starting point for a new generation sequence to be completed on the following card. If the generation sequence is to end on a node that has been previously defined, MODEG = 3 must be used instead of MODEG = 2. If MODEG = 1 or 3 is specified, XCOORD and YCOORD need not be input since these values are already known.

Lastly, the option MODEG = 5 permits one to assign nonsequential node numbers to a generated sequence. In other words, MODEG = 5 takes the place of sequencing the nodal numbers with the parameter NPINC. To use MODEG = 5, first specify the starting node as always done, i.e., MODEG = 0 or 1. Then insert MODEG = 5 cards back-to-back, entering each intervening node number in the entry NNP. For the last node in the sequence, use MODEG = 2 or 3 and define the generation desired.

Note, node numbers can be input in any sequence; all nodes unspecified on nodal cards but appearing on element cards will have coordinates automatically generated by an averaging technique called Laplace generation.

(10) Four element types are available with the CANDE program: continuum quadrilateral, continuum triangle, beam/column (i.e., pipe element), and interface element. The element type is inherently specified by the manner in which the element connectivity array, IX(1), IX(2), IX(3), and IX(4), is defined:

(a) Quadrilaterals - set IX(1), IX(2), IX(3), and IX(4) to the node numbers connected to the element in counterclockwise order

(b) Triangles - set IX(1), IX(2), and IX(3) to the node numbers connected to the element in counterclockwise order. Leave IX(4) = 0

(c) Beam/columns - set IX(1) and IX(2) to node numbers at the beam ends, such that, when traveling from IX(1) to IX(2), the pipe interior is on the right. Leave IX(3) = IX(4) = 0

(d) Interface - set IX(1) and IX(2) to separate node numbers with the same coordinates on either side of a common interface. Set IX(3) to a node number unused by any other element (this node is associated with interface forces). Set IX(4) = 0 and IX(7) = 1 to distinguish from triangle

These elements are illustrated in Figure II-10.

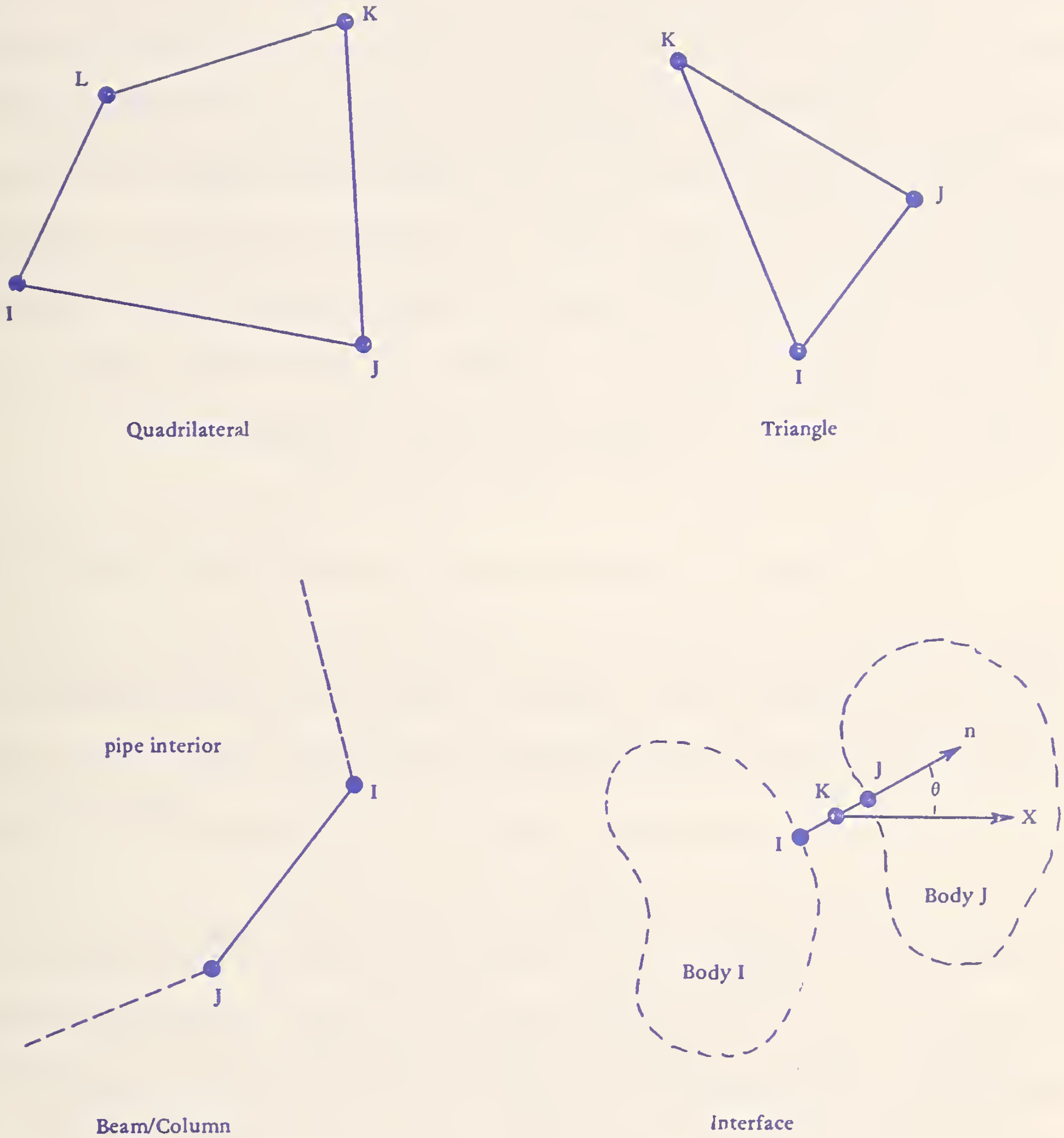


Figure II-10. Types of CANDE elements.

(11) The element material number, IX(5), identifies groups of elements with common material properties. Material numbers associated with one element type are unrelated to another element type, except continuum elements (quadrilateral and triangle) share common material numbers. The material numbering for beam/column elements (i.e., pipe elements) is a special case and must be defined as follows. Each pipe element is given a separate material number beginning with 1 and proceeding clockwise around the pipe in a connected sequence. This special numbering scheme is required for evaluating the pipe responses.

(12) The element generation options require serial input of element numbers. Element numbers that are skipped between successive input cards will be automatically generated, such that the node connectivity of each generated element is determined by adding INTRAL to the nodes I, J, K, and L of the previous element in the sequence. The material number and construction increment remain as specified by the first element in the sequence. If it is desired to change the material number and/or construction increment during the sequence generation, insert intervening card(s) specifying only NE, IX(5), and IX(6) of the element where the change occurs, i.e., do not input connectivity.

(13) To extend the generation to more than one row of elements, simply identify the number of rows to be generated (NUMLAY), and specify the node number increment from one row to the next INTERL (generally this would be the number of elements in a row plus one).

(14) Unless specified differently on this card, every node is assumed to be unrestrained with zero external forces acting on it (i.e., IIFLG(1) = IIFLG(2) = 0, and BIVD(1) = BIVD(2) = 0.0). To apply displacement constraints, concentrated strip loads, and pressures, repeat this card as required. Note, every node has two displacement degrees of freedom. The boundary condition for each degree of freedom is either an imposed external force (IIFLG = 0), or an imposed displacement (IIFLG = 1). The additional rotational degree of freedom associated with nodes of the beam/column element is unrestrained only if both displacements of the node are unrestrained. Otherwise, a nonrotational end restraint is automatically imposed.

(15) All boundary conditions are referenced to the global coordinate system. To reference the boundary conditions to a skewed system, define the angle, THETA.

(16) To generate a sequence of identical boundary conditions, the node NP is first in the sequence and NNP is the last. Boundary conditions are automatically generated for intervening node numbers; NP + INCR, NP + 2·INCR, etc., where INCR is positive for increasing numbers and negative for decreasing numbers.

(17) Pressure loads can be specified over any connected sequence of nodes by specifying a constant or linearly varying pressure from

node NP to node NNP. Pressure is normal to each line segment, and positive values point to left in traveling from NP to NNP. For pressure generation, set IIFLG(1) = IIFLG(2) = 0.

The same boundary node NP may be specified again on subsequent cards under the following rules: (1) Force boundary conditions add into the BIVD vector; (2) it is permissible to override any predefined force boundary condition with a displacement boundary condition, but not vice versa (it's good practice to first define force boundary conditions, then displacement boundary conditions); (3) boundary conditions are not activated until the load step equals IA. During this step the value BIVD is applied to the system and, thereafter, set to zero for subsequent steps.

Every time a boundary node is referenced or generated it counts as one more boundary condition for computing the total number of boundary conditions.

Boundary conditions for interface element nodes I and J represent displacement degrees of freedom and are treated as discussed above. However, node K represents interface forces where the boundary code is defined as:

IIFLG(1) = 0, normal force unknown (typical)

IIFLG(1) = 1, normal force specified by BIVD(1)

IIFLG(2) = 0, shear force unknown (typical)

IIFLG(2) = 1, shear force specified by BIVD(2)

Normally node K of interface elements is not specified in boundary condition input. However, if corresponding displacement degrees of freedom of nodes I and J are both restrained to zero, then the corresponding interface force must also be restrained to zero.

PART III

EXAMPLE PROBLEMS

The example problems presented herein are strictly to demonstrate data input and data output. Accordingly, the problems are contrived to illustrate various modeling options. They are not necessarily intended as design recommendations.

The six examples considered are identified in Table III-1 by execution mode, pipe type, solution level, installation type, and special comments.

In subsequent pages, each problem is presented in the following format: (1) a listing of all input data cards defining the problem, and (2) selected CANDE output identifying the input parameters and illustrating structural responses and pipe evaluation. For brevity, soil response output is omitted. Unless otherwise noted the units of response data are in the inch-pound system. For reference, Table III-2 lists output symbols with their definitions and units; Tables III-3, III-4, III-5, and III-6 identify the design and evaluation factors for corrugated steel, corrugated aluminum, reinforced concrete, and plastic pipe, respectively.

Table III-1. Example Problem Identification

Problem No.	Execution Mode	Pipe Type	Solution Level	Soil System	Special Comment
1	design	steel	1	homogeneous	Yield-hinge theory
2	analysis	steel	2	embankment	Backpacking included equivalent surface pressure
3	design	concrete	1	homogeneous	Fixed-wall design, overburden dependent
4	design	aluminum	2 extended	trench	Concentrated load on surface, gravity trench fill
5	analysis	plastic	2	homogeneous	Slip interface, gravity loading
6	analysis	concrete	3	none	D-load test; i.e., two-point bearing

Table III-2. CANDE Output Symbols

Symbol	Units	Description
ANG	deg	Rotation to coordinates for principal stresses
EPSILON-X	in./in.	Strain in x-coordinate direction (soil)
EPSILON-Y	in./in.	Strain in y-coordinate direction (soil)
GAMA-XY	in./in.	Engineering shear strain in x-y coordinate plane (soil)
MOMENT	in.-lb/in.	Bending moment in pipe wall section per unit length
M-STRESS	psi	Outer fiber stress due to the bending moment
N-PRES	psi	Normal pressure acting on pipe periphery (i.e., soil pressure)
SHEAR	lb/in.	Resultant shear force acting on pipe section
S-STRESS	psi	Shear stress on pipe wall cross section
S-PRES	psi	Traction pressure acting on pipe periphery (soil shear on pipe)
SIGMA-X	psi	Stress in x-coordinate direction (soil)
SIGMA-Y	psi	Stress in y-coordinate direction (soil)
SIGMA-1	psi	Maximum principal stress (soil)
SIGMA-2	psi	Minimum principal stress (soil)
TAU-XY	psi	Shear stress in x-y coordinate plane (soil)
THRUST	lb/in.	Resultant circumferential force in pipe wall
T-STRESS	psi	Thrust divided pipe sectional area
X-COORD	in.	Node location of x-coordinate in undeformed state
X-DISP	in.	Displacement from undeformed position in x-direction
Y-COORD	in.	Node location of y-coordinate in undeformed state
Y-DISP	in.	Displacement from undeformed position in y-direction

Table III-3. Evaluation Output for Corrugated Steel

Design and Evaluation Items	Definition of Item
Thrust yielding safety factor	Yield stress of steel divided by maximum thrust stress in pipe wall section
Displacement collapse safety factor	Twenty percent of average diameter divided by maximum relative displacement of pipe
Elastic buckling safety factor	Critical elastic buckling pressure divided by average normal pressure experienced by the pipe
Bending stress performance	Yield stress of steel divided by bending stress (a value of 1.0 indicates yielding and is permissible)
Handling performance factor	Should have FF > D^2/EI, where FF = 0.043, or 0.02 for structural plate corrugation [D = pipe diameter and EI = pipe bending stiffness (elastic)]
Design output	Wall area (in.^{2}/in.) Moment of inertia (in.^{4}/in.) Section modulus (in.^{3}/in.) List of suitable corrugations

Table III-4. Evaluation Output for Corrugated Aluminum

Design and Evaluation Items	Definition of Item
Thrust yielding safety factor	Yield stress of aluminum divided by maximum thrust stress in pipe wall section
Displacement collapse safety factor	Twenty percent of average diameter divided by maximum relative displacement of pipe
Elastic buckling safety factor	Critical elastic buckling pressure divided by average normal pressure experienced by the pipe
Outer fiber rupture safety factor	Strain causing aluminum rupture divided by maximum outer fiber strain due to thrust and bending
Bending stress performance factor	Yield stress of aluminum divided by bending stress (a value of 1.0 indicates yielding and is permissible)
Handling performance	Should have FF > D^2/EI, where FF = 0.09, or 0.042 for structural plate [D = pipe diameter and EI = pipe bending stiffness (elastic)]
Design output	Wall area (in.^{2}/in.) Moment of inertia (in.^{4}/in.) Section modulus (in.^{3}/in.) List of suitable corrugations

Table III-5. Evaluation Output for Reinforced Concrete

Design and Evaluation Items	Definition of Item
Reinforcement yielding safety factor	Yield stress of steel reinforcement divided by absolute maximum stress in the steel cage(s)
Concrete crushing safety factor	Compressive strength of concrete, f'_c, divided by maximum compressive stress in outer fibers
Shear cracking safety factor	Wall shear strength (i.e., concrete tensile strength) divided by maximum shear stress at axis of bending
Allowable crack-width performance factor	Crack width of 0.01 inch divided by maximum predicted crack width occurring at location of maximum steel stress
Allowable displacement performance factor	Allowable pipe deflection = $D^2/1200h$, where D = diameter and h = wall thickness. Factor = allowable/actual
Bow stringing performance factor	Tensile strength of concrete ($5\sqrt{f'_c}$), divided by a high estimate of tensile stress between steel and concrete
Design output	Required wall thickness (in.) Required steel areas for circular or elliptical cages (in.^{2}/in.)

Table III-6. Evaluation Output for Plastic Pipe

Design and Evaluation Items	Definition of Item
Displacement collapse safety factor	Twenty percent of diameter divided by maximum relative displacement of pipe
Outer fiber ultimate stress safety factor	Ultimate stress of plastic material divided by predicted maximum outer fiber stress
Elastic buckling safety factor	Critical elastic buckling pressure divided by average normal pressure experienced by the pipe
Handling performance factor	Must have $FF > D^2/EI$, where $FF = 0.333$ [D = pipe diameter and EI = pipe handling stiffness (elastic)]
Design output	Required wall thickness (in.)

Problem 1 – Input

```
              INPUT CARDS FOR PROBLEM NUMBER  1

CARD TYPE     1...+...10...+...20...+...30...+...40...+...50...+...60...+...70...+...80

  CARD 1A     DESIGN 1 STEEL      FILL COVER 30 FEET, 60-INCH PIPE, 1-LIFT.
  CARD 1B        1       60.0
  CARD 2B           2.0
  CARD 1C         120.0
  CARD 2C          30.0     1000.0      0.35
```

Problem 1 – Output

```
*** PROBLEM NUMBER  1 ***

  FILL COVER 30 FEET, 60-INCH PIPE, 1-LIFT.

EXECUTION MODE .....DESI

SOLUTION LEVEL .....BURNS

CULVERT TYPE ...... STEEL


PIPE PROPERTIES ARE AS FOLLOWS ...

     AVERAGE PIPE DIAMETER (IN.) .......     .60000E+02

     YOUNGS MODULUS OF PIPE (PSI) ......     .30000E+08

     POISSONS RATIO OF PIPE (-) ........     .30000E+00

     YIELD STRESS OF PIPE (PSI) ........     .33000E+05

     DENSITY OF PIPE (PCI) ............   -0.

     MATERIAL CHARACTER, NONLIN ........    1
       NONLIN=0, IMPLIES LINEAR
       NONLIN=1, IMPLIES YIELD-HINGE
       NONLIN=2, IMPLIES BILINEAR CURVE


DESIRED SAFETY FACTORS FOR PIPE DESIGN ...

     THRUST STRESS YIELDING ............   2.00000

     DEFLECTION COLLAPSE,(0.2*D) .......   4.00000

     ELASTIC BUCKLING ..................   2.00000
```

Problem 1 – Output (cont'd)

SYSTEM PROPERTIES ARE AS FOLLOWS...

DENSITY OF FILL MATERIAL (PCF) 120.000

NO. OF DATA POINTS ON HALF PIPE ... 11

NUMBER OF LOAD INCREMENTS 1

SLIP, NO SLIP INTERFACE OPTION .... NO SLIP

MATERIAL PROPERTIES OF SOIL IN VICINITY OF
CULVERT AS A FUNCTION OF SOIL HEIGHT.

LOAD STEP	SOIL HEIGHT (FEET)	CONFINED MODULUS (PSI)	LATERIAL STRESS RATIO	YOUNGS MODULUS (PSI)	POISSONS RATIO
1	30.00	1604.94	.54	1000.00	.350

```
DESIGN RESULTS AT  2 ITERATIONS

     *** REQUIRED THRUST AREA .........    .05691

     *** REQUIRED MOM. OR INERTIA .....    .00277

     *** REQUIRED SECTION MODULUS .....    .00804


THE FOLLOWING STEEL CORRUGATED SECTIONS MEET THE
ABOVE REQUIREMENTS WITH MINIMUM AREA

     CORRUGATION    GAGE    THRUST AREA    MOM. INERTIA

       3/2 X  1/4      (NO ADEQUATE SECTION)
        2  X  1/2       12          .11900          .00354
       8/3 X  1/2       12          .11300          .00342
         3 X  1         18          .05925          .00689
         6 X  2         12          .12966          .06041


THE CORRUGATION WITH MINIMUM AREA AND
MOMENT OF INERTIA IS   3 X  1   GAGE, 18
AN ANALYSIS OF THIS CORRUGATION FOLLOWS.
```

STRUCTURAL RESPONSES OF CULVERT   LOAD STEP = 1

X-COORD.	X-DISP.	N-PRES.	MOMENT	THRUST	SHEAR
Y-COORD.	Y-DISP.	S-PRES.	M-STRESS	T-STRESS	S-STRESS
-.00	.105E-16	-.196E+02	.363E+03	-.539E+03	-.836E-13
30.00	-.494E+00	.434E-13	.276E+05	-.910E+04	-.141E-11
9.27	.115E-01	-.206E+02	.293E+03	-.578E+03	.143E+02
28.53	-.426E+00	-.744E+01	.223E+05	-.976E+04	.242E+03
17.63	.925E-01	-.231E+02	.110E+03	-.679E+03	.232E+02
24.27	-.266E+00	-.120E+02	.837E+04	-.115E+05	.391E+03
24.27	.247E+00	-.263E+02	-.116E+03	-.804E+03	.232E+02
17.63	-.106E+00	-.120E+02	-.881E+04	-.136E+05	.391E+03
28.53	.405E+00	-.289E+02	-.299E+03	-.905E+03	.143E+02
9.27	-.186E-01	-.744E+01	-.227E+05	-.153E+05	.242E+03
30.00	.471E+00	-.298E+02	-.368E+03	-.944E+03	-.260E-12
-.00	.762E-16	.135E-12	-.280E+05	-.159E+05	-.438E-11
28.53	.405E+00	-.289E+02	-.299E+03	-.905E+03	-.143E+02
-9.27	.186E-01	.744E+01	-.227E+05	-.153E+05	-.242E+03
24.27	.247E+00	-.263E+02	-.116E+03	-.804E+03	-.232E+02
-17.63	.106E+00	.120E+02	-.881E+04	-.136E+05	-.391E+03
17.63	.925E-01	-.231E+02	.110E+03	-.679E+03	-.232E+02
-24.27	.266E+00	.120E+02	.837E+04	-.115E+05	-.391E+03
9.27	.115E-01	-.206E+02	.293E+03	-.578E+03	-.143E+02
-28.53	.426E+00	.744E+01	.223E+05	-.976E+04	-.242E+03
.00	-.457E-16	-.196E+02	.363E+03	-.539E+03	-.263E-12
-30.00	.494E+00	.137E-12	.276E+05	-.910E+04	-.443E-11

```
CALCULATED SAFETY FACTORS AT STEP  1

     THRUST STRESS ....... (YIELD-STRESS/MAX-STRESS) =       2.07
     DISPLACEMENT ......... (DIAMETER*0.2/MAX-DISP.) =      12.14
     ELASTIC BUCKLING ....... (P-CRITICAL/P-AVERAGE) =       6.90

PERFORMANCE FACTORS

     BENDING STRESS ...... (YIELD-STRESS/MAX-STRESS) =       1.18
     HANDLING REQUIREMENT ............. (FF*EI/D**2) =       2.49
```

Problem 2 — Input

```
                INPUT CARDS FOR PROBLEM NUMBER  2

CARD TYPE       1....*...10....*...20....*...30....*...40....*...50....*...60....*...70....*...80
  CARD 1A       ANALYS 2 STEEL     OVERBURDEN LOADING, 3 X 1 CORRUGATION 12-GAGE.
  CARD 1B           2      60.0
  CARD 2B          0.13    0.01545   0.02798
  CARD 1C       EMBA      EMBANKMENT MESH WITH SOFT BACKPACKING.
  CARD 2C                1        -1            32.5                   25.0
  CARD 3C          10
  CARD 1D           1    1             INSITU (LINEAR)
  CARD 2D          1000.0     0.35
  CARD 1D           2    1           BEDDING = INSITU
  CARD 2D          1000.0     0.35
  CARD 1D           3    1              FILL = INSITU
  CARD 2D          1000.0     0.35
  CARD 1D       L   4    1           PACKING = INSITU/2
  CARD 2D           500.0     0.35
```

```
*** PROBLEM NUMBER  2 ***

  OVERBURDEN LOADING, 3 X 1 CORRUGATION 12-GAGE.

EXECUTION MODE .....ANAL

SOLUTION LEVEL .....F.E.AUTO

CULVERT TYPE ...... STEEL


PIPE PROPERTIES ARE AS FOLLOWS ...

     AVERAGE PIPE DIAMETER (IN.) .......     .60000E+02

     YOUNGS MODULUS OF PIPE (PSI) ......     .30000E+08

     POISSONS RATIO OF PIPE (-) ........     .30000E+00

     YIELD STRESS OF PIPE (PSI) ........     .33000E+05

     DENSITY OF PIPE (PCI) ............    -0.

     MATERIAL CHARACTER, NONLIN ........    2
       NONLIN=0, IMPLIES LINEAR
       NONLIN=1, IMPLIES YIELD-HINGE
       NONLIN=2, IMPLIES BILINEAR CURVE


     MODULUS OF UPPER BI-CURVE .........    -0.


SECTION PROPERTIES OF PIPE ...

     THRUST AREA (IN**2/IN) ...........     .13000

     MOM. OF INERTIA (IN**4/IN) ........     .01545

     SECTION MODULUS (IN**3/IN) ........     .02798
```

```
* * BEGIN GENERATION OF CANNED MESH * *


THE DATA TO BE RUN IS ENTITLED

     EMBANKMENT MESH WITH SOFT BACKPACKING.

TYPE OF MESH------------------------- EMBANKMENT

PLOTTING DATA SAVED------------------    -0

PRINT SOIL RESPONSES-----------------     1

PRINT CONTROL FOR PREP OUTPUT---------   -0

NUMBER OF CONSTRUCTION INCREMENTS-----    1

PIPE DIAMETER RATIO-------------------     1.00

LIVE LOAD PRESSURE ON LAST INCR.------    25.00

NUMBER OF BACKPACKING ELEMENTS--------   10

WIDTH OF BACKPACKING LAYER------------     5.00

SOIL HEIGHT ABOVE SPRINGLINE (FEET)---    32.50

MESH HEIGHT ABOVE SPRINGLINE (FEET)---    10.00

SOIL DENSITY ABOVE MESH (PCF)---------    -0.00

PRESSURE OF TRUNCATED SOIL (PSI)------     0.00


IDENTIFICATION OF MATERIAL ZONE WITH MATERIAL NUMBERS.

          MATERIAL-ZONE    MATERIAL NO.

               INSITU        1
               BEDDING       2
               BACKFILL      3
               BACKPACK      4
```

```
* * BEGIN PREP OF FINITE ELEMENT INPUT * *

THE DATA TO BE RUN IS ENTITLED

     EMBANKMENT MESH WITH SOFT BACKPACKING,

NUMBER OF CONSTRUCTION INCREMENTS......      1
PRINT CONTROL FOR PREP OUTPUT..........     -0
INPUT DATA CHECK.......................      0
PLOT TAPE GENERATION...................     -0
ENTIRE FINITE ELEMENT RESULTS OUTPUT...      1
THE NUMBER OF NODES IS.................    110
THE NUMBER OF ELEMENTS IS..............     96
THE NUMBER OF BOUNDARY CONDITIONS IS...     45
```

```
* * * * * * FOR MESH GENERATION OF * * * * * *

     EMBANKMENT MESH WITH SOFT BACKPACKING.

THE NUMBER OF DATA ERRORS IS...........     0
THE NUMBER OF SOIL MATERIALS IS........     4
THE NUMBER OF PIPE MATERIALS IS........    10
THE NUMBER OF INTERFACE MATERIALS IS...     0
THE BAND WIDTH IS......................    26
* * * * * * * MESH DATA HAS BEEN SAVED * * * * * * *

          AN ORDERED LIST OF BEAM ELEMENTS AROUND PIPE,
          ORDERING IS CLOCKWISE FROM TOP TO BOTTOM OR LEFT TO RITE.

             1    2    3    4    5    6    7    8    9   10
```

```
MATERIAL CHARACTERIZATION FOR SOILS.


PROPERTIES FOR MATERIAL  1   ******** INSITU (LINEAR)

     DENSITY =   -0.

      YOUNGS MODULUS=   .1000E+04
      POISSONS RATIO=   .3500E+00
      CONFINED MOD.=    .1605E+04
      LATERAL COEFF.=   .5385E+00


PROPERTIES FOR MATERIAL  2   ********BEDDING = INSITU

     DENSITY =   -0.

      YOUNGS MODULUS=   .1000E+04
      POISSONS RATIO=   .3500E+00
      CONFINED MOD.=    .1605E+04
      LATERAL COEFF.=   .5385E+00


PROPERTIES FOR MATERIAL  3   ********   FILL = INSITU

     DENSITY =   -0.

      YOUNGS MODULUS=   .1000E+04
      POISSONS RATIO=   .3500E+00
      CONFINED MOD.=    .1605E+04
      LATERAL COEFF.=   .5385E+00


PROPERTIES FOR MATERIAL  4   ********PACKING = INSITU/2

     DENSITY =   -0.

      YOUNGS MODULUS=   .5000E+03
      POISSONS RATIO=   .3500E+00
      CONFINED MOD.=    .8025E+03
      LATERAL COEFF.=   .5385E+00
```

Problem 2 — Output (cont'd)

STRUCTURAL RESPONSES OF CULVERT   LOAD STEP = 1

X-COORD. Y-COORD.	X-DISP. Y-DISP.	N-PRES. S-PRES.	MOMENT M-STRESS	THRUST T-STRESS	SHEAR S-STRESS
0.00	0.	-.219E+02	.809E+03	-.542E+03	0.
30.00	-.232E+01	0.	.289E+05	-.417E+04	0.
9.27	.904E-02	-.222E+02	.650E+03	-.581E+03	.301E+02
28.53	-.225E+01	-.515E+01	.232E+05	-.447E+04	.232E+03
17.63	.853E-01	-.228E+02	.243E+03	-.657E+03	.479E+02
24.27	-.210E+01	-.816E+01	.869E+04	-.505E+04	.368E+03
24.27	.233E+00	-.240E+02	-.249E+03	-.749E+03	.477E+02
17.63	-.195E+01	-.814E+01	-.889E+04	-.576E+04	.367E+03
28.53	.384E+00	-.246E+02	-.652E+03	-.824E+03	.296E+02
9.27	-.187E+01	-.499E+01	-.233E+05	-.634E+04	.227E+03
30.00	.447E+00	-.249E+02	-.804E+03	-.851E+03	-.343E+00
0.00	-.186E+01	.141E+00	-.287E+05	-.655E+04	-.264E+01
28.53	.382E+00	-.246E+02	-.645E+03	-.822E+03	-.299E+02
-9.28	-.185E+01	.504E+01	-.231E+05	-.632E+04	-.230E+03
24.27	.231E+00	-.239E+02	-.242E+03	-.747E+03	-.479E+02
-17.64	-.177E+01	.814E+01	-.863E+04	-.575E+04	-.369E+03
17.63	.841E-01	-.230E+02	.254E+03	-.655E+03	-.472E+02
-24.27	-.162E+01	.810E+01	.909E+04	-.504E+04	-.363E+03
9.27	.883E-02	-.221E+02	.644E+03	-.581E+03	-.286E+02
-28.53	-.147E+01	.492E+01	.230E+05	-.447E+04	-.220E+03
0.00	0.	-.217E+02	.791E+03	-.544E+03	0.
-30.00	-.140E+01	0.	.283E+05	-.418E+04	0.

NONLINEAR CHARACTERISTICS, LOAD STEP = 1

NODE	INNER-FIBER STRAIN	OUTER-FIBER STRAIN	STRAIN RATIO MAX-TO-YIELD	FRACTION OF WALL YIELDED
1	.75042E-03	-.10035E-02	1.00249	.00142
2	.56937E-03	-.84049E-03	.83965	0.00000
3	.11049E-03	-.41687E-03	.41646	0.00000
4	-.44441E-03	.94825E-04	.44396	0.00000
5	-.89898E-03	.51457E-03	.89808	0.00000
6	-.10700E-02	.67274E-03	1.06898	.03962
7	-.89148E-03	.50791E-03	.89059	0.00000
8	-.43618E-03	.87593E-04	.43574	0.00000
9	.12308E-03	-.42863E-03	.42820	0.00000
10	.56278E-03	-.83387E-03	.83304	0.00000
11	.73067E-03	-.98444E-03	.98345	0.00000

```
CALCULATED SAFETY FACTORS AT STEP  1

     THRUST STRESS ....... (YIELD-STRESS/MAX-STRESS) =      5.04

     DISPLACEMENT ......... (DIAMETER*0.2/MAX-DISP.) =     13.15

     ELASTIC BUCKLING ....... (P-CRITICAL/P-AVERAGE) =     10.35

PERFORMANCE FACTORS

     BENDING STRESS ...... (YIELD-STRESS/MAX-STRESS) =      1.14

     HANDLING REQUIREMENT ............. (FF*EI/D**2) =      5.57
```

```
                INPUT CARDS FOR PROBLEM NUMBER  3

CARD TYPE       1...+...10....+...20....+...30....+...40....+...50....+...60....+...70....+...80

  CARD 1A       DESIGN 1 CONCRE     FILL COVER 30 FEET IN 3 LIFTS, FIXED WALL DESIGN.
  CARD 1B             60.0        6.0         3
  CARD 2B                                                        60000.
  CARD 3B                                                  0.01         FIX
  CARD 1C            120.0     3
  CARD 2C             10.0       700.0        0.35
  CARD 2C             20.0       900.0        0.35
  CARD 2C             30.0      1000.0        0.35
```

Problem 3 — Output

```
*** PROBLEM NUMBER  3 ***

  FILL COVER 30 FEET IN 3 LIFTS, FIXED WALL DESIGN.

EXECUTION MODE .....DESI

SOLUTION LEVEL .....BURNS

CULVERT TYPE ...... CONCRETE
```

```
PIPE PROPERTIES ARE AS FOLLOWS ...
(UNITS ARE INCH-POUND SYSTEM )

     NOMINAL PIPE DIAMETER .............          60.0000

     CONCRETE COMPRESSIVE STRENGTH .....        4000.0000

     CONCRETE ELASTIC MODULUS ..........     3830253.5127

     CONCRETE POISSON RATIO ............            .1700

     STEEL YIELD STRENGTH ..............       60000.0000

     STEEL ELASTIC MODULUS .............    29000000.0000

     STEEL POISSON RATIO ...............            .3000

     NONLINEAR CODE (1,2,OR 3) .........                3

     CONC. CRACKING STRAIN (1,2,3) .....         0.000000

     CONC. YIELDING STRAIN (2,3) .......          .000507

     CONC. CRUSHING STRAIN (2,3) .......          .002000

     STEEL YIELDING STRAIN (3) .........          .001883

DESIRED SAFETY FACTORS FOR PIPE DESIGN ...

     STEEL YIELDING ....................           1.6000

     CONCRETE CRUSHING .................           2.0000

     CONCRETE SHEAR FAILURE ............           2.0000

     ALLOWABLE CRACK WIDTH (IN) .......            .0100

     SHAPE OF REBAR CAGE(S) ............             CIRC

     MIN. COVER TO CENTER OF REBAR .....           1.2500

     DESIGN GOAL FOR WALL THICKNESS ....              FIX

     FIXED WALL THICKNESS ..............           6.0000

     OUTER-TO-INNER STEEL RATIO ........            .7500
```

SYSTEM PROPERTIES ARE AS FOLLOWS...

DENSITY OF FILL MATERIAL (PCF)	120.000
NO. OF DATA POINTS ON HALF PIPE ...	11
NUMBER OF LOAD INCREMENTS	3
SLIP, NO SLIP INTERFACE OPTION	NO SLIP

MATERIAL PROPERTIES OF SOIL IN VICINITY OF
CULVERT AS A FUNCTION OF SOIL HEIGHT.

LOAD STEP	SOIL HEIGHT (FEET)	CONFINED MODULUS (PSI)	LATERIAL STRESS RATIO	YOUNGS MODULUS (PSI)	POISSONS RATIO
1	10.00	1123.46	.54	700.00	.350
2	20.00	1444.44	.54	900.00	.350
3	30.00	1604.94	.54	1000.00	.350

Problem 3 — Output (cont'd)

```
DESIGN RESULTS A,  5 ITERATIONS

     *** WALL THICKNESS ................   6.00000

     *** INNER CAGE STEEL AREA (OR ELLI)    .03974

     *** OUTER CAGE STEEL AREA .........    .02981
```

STRUCTURAL RESPONSE OF CULVERT FOR LOAD INCREMENT 3

COORDINATES, DISPLACEMENTS AND CRACK DEPTHS ARE IN INCHES
PRESSURES ARE IN LB/IN**2
MOMENTS ARE IN IN.*LB/IN.
THRUST AND SHEAR ARE IN LB/IN.

NPPT	X-COORD. Y-COORD.	X-DISP. Y-DISP.	N-PRES. S-PRES.	MOMENT THRUST	SHEAR CRACK DEPTH
1	-.00 33.00	.37095E-17 -.95766E-01	-.31595E+02 .34272E-13	.41902E+04 -.52976E+03	-.87965E-12 .42954E+01
2	10.20 31.38	.20618E-02 -.82676E-01	-.30323E+02 -.58727E+01	.33821E+04 -.58573E+03	.15073E+03 .42022E+01
3	19.40 26.70	.17517E-01 -.51616E-01	-.26993E+02 -.95022E+01	.12665E+04 -.73227E+03	.24389E+03 .34639E+01
4	26.70 19.40	.47240E-01 -.20697E-01	-.22876E+02 -.95022E+01	-.13485E+04 -.91340E+03	.24389E+03 .36058E+01
5	31.38 10.20	.77532E-01 -.37333E-02	-.19546E+02 -.58727E+01	-.34641E+04 -.10599E+04	.15073E+03 .41800E+01
6	33.00 -.00	.90357E-01 .17300E-16	-.18274E+02 .10649E-12	-.42722E+04 -.11159E+04	-.27332E-11 .42519E+01
7	31.38 -10.20	.77532E-01 .37333E-02	-.19546E+02 .58727E+01	-.34641E+04 -.10599E+04	-.15073E+03 .41800E+01
8	26.70 -19.40	.47240E-01 .20697E-01	-.22876E+02 .95022E+01	-.13485E+04 -.91340E+03	-.24389E+03 .36058E+01
9	19.40 -26.70	.17517E-01 .51616E-01	-.26993E+02 .95022E+01	.12665E+04 -.73227E+03	-.24389E+03 .34639E+01
10	10.20 -31.38	.20618E-02 .82676E-01	-.30323E+02 .58727E+01	.33821E+04 -.58573E+03	-.15073E+03 .42022E+01
11	.00 -33.00	-.11658E-16 .95766E-01	-.31595E+02 .10771E-12	.41902E+04 -.52976E+03	-.27646E-11 .42954E+01

STRESSES IN CULVERT WALL (PSI) FOR LOAD INCREMENT 3

NPPT	ELLIP. OR INNER CAGE STEEL	OUTER CAGE STEEL	CONCRETE COMPRESSION	SHEAR STRESS
1	.22774E+05	-.33997E+04	-.15794E+04	-.21228E-12
2	.17790E+05	-.33013E+04	-.13423E+04	.36979E+02
3	.47139E+04	-.27383E+04	-.66902E+03	.70994E+02
4	-.32207E+04	.66309E+04	-.83496E+03	.29411E+02
5	-.43888E+04	.22559E+05	-.17362E+04	.57772E+01
6	-.47453E+04	.28599E+05	-.20215E+04	-.46266E-13
7	-.43888E+04	.22559E+05	-.17362E+04	-.57772E+01
8	-.32207E+04	.66309E+04	-.83496E+03	-.29411E+02
9	.47139E+04	-.27383E+04	-.66902E+03	-.70994E+02
10	.17790E+05	-.33013E+04	-.13423E+04	-.36979E+02
11	.22774E+05	-.33997E+04	-.15794E+04	-.66716E-12

```
CALCULATED SAFETY FACTORS FOR LOAD INCREMENT     3

     STEEL YIELD STRESS / MAX. STEEL STRESS .........      2.098
     CONCRETE STRENGTH / MAX. COMPRESSIVE STRESS ....      1.979
     WALL SHEAR CAPACITY / MAX. SHEAR ..............       4.054
PERFORMANCE FACTORS
     0.01 INCH / MAX. CRACK WIDTH ..................        .974
     ALLOWABLE DISPLACEMENT(LUM) / MAX. DISP. .......      2.611
     TENSILE STRENGTH / STRESS FROM BOW STRING ......       .918
```

```
              INPUT CARDS FOR PROBLEM NUMBER  4

CARD TYPE     1...*...10....*...20....*...30....*...40....*...50....*...60....*...70....*...80

  CARD 1A     ANALYS 2 PLASTI    FILL COVER = 20 FEET, 48-INCH PIPE, FRICTION FACE,
  CARD 1B            48.0
  CARD 2B            0.50
  CARD 1C     HOMO      INCLUDE INTERFACE ELEMENTS FOR FRICTION = 0.1                     SLIP
  CARD 2C               1         -1                   22.0      120.0
  CARD 3C         0
  CARD 1D         1     1      120.0     HOMOGENEOUS SOIL
  CARD 2D         1000.0      0.35
  CARD 1D         1     6
  CARD 2D          -90.0       0.1
  CARD 1D         2     6
  CARD 2D          -72.0       0.1
  CARD 1D         3     6
  CARD 2D          -54.0       0.1
  CARD 1D         4     6
  CARD 2D          -36.0       0.1
  CARD 1D         5     6
  CARD 2D          -18.0       0.1
  CARD 1D         6     6
  CARD 2D           0.00       0.1
  CARD 1D         7     6
  CARD 2D           18.0       0.1
  CARD 1D         8     6
  CARD 2D           36.0       0.1
  CARD 1D         9     6
  CARD 2D           54.0       0.1
  CARD 1D        10     6
  CARD 2D           72.0       0.1
  CARD 1D     L  11     6
  CARD 2D           90.0       0.1
```

Problem 4 — Output

```
*** PROBLEM NUMBER  4 ***

  FILL COVER = 20 FEET, 48-INCH PIPE, FRICTION FACE.

EXECUTION MODE .....ANAL

SOLUTION LEVEL .....F.E.AUTO

CULVERT TYPE ...... PLASTIC


PIPE PROPERTIES ARE AS FOLLOWS ...

     AVERAGE PIPE DIAMETER (IN.) ........        48.00

     YOUNGS MODULUS OF PIPE (PSI) ...... 1600000.00

     POISSONS RATIO OF PIPE (-) ........           .30

     YIELD STRESS OF PIPE (PSI) ........    25000.00

     DENSITY OF PIPE (PCI) .............          -0.00


SECTION PROPERTIES OF PIPE ...

     THICKNESS OF PIPEWALL (IN).........     .50000

     THRUST AREA (IN**2/IN) ............     .50000

     MOM. OF INERTIA (IN**4/IN) ........     .01042

     SECTION MODULUS (IN**3/IN) ........     .04167
```

```
* * BEGIN GENERATION OF CANNED MESH * *

THE DATA TO BE RUN IS ENTITLED

     INCLUDE INTERFACE ELEMENTS FOR FRICTION = 0.1

TYPE OF MESH------------------------ HOMOGENOUS

PLOTTING DATA SAVED-----------------     =0

PRINT SOIL RESPONSES----------------      1

PRINT CONTROL FOR PREP OUTPUT--------    =0

NUMBER OF CONSTRUCTION INCREMENTS----     1

PIPE DIAMETER RATIO------------------      1.00

LIVE LOAD PRESSURE ON LAST INCR.-----     -0.00

SOIL HEIGHT ABOVE SPRINGLINE (FEET)--     22.00

MESH HEIGHT ABOVE SPRINGLINE (FEET)--      8.08

SOIL DENSITY ABOVE MESH (PCF)--------    120.00

PRESSURE OF TRUNCATED SOIL (PSI)-----     11.60


IDENTIFICATION OF MATERIAL ZONE WITH MATERIAL NUMBERS.

          MATERIAL-ZONE     MATERIAL NO.

               INSITU       1
               BEDDING      1
               BACKFILL     1
```

```
* * BEGIN PREP OF FINITE ELEMENT INPUT * *

THE DATA TO BE RUN IS ENTITLED

     INCLUDE INTERFACE ELEMENTS FOR FRICTION = 0.1

NUMBER OF CONSTRUCTION INCREMENTS------     1
PRINT CONTROL FOR PREP OUTPUT----------    -0
INPUT DATA CHECK-----------------------     0
PLOT TAPE GENERATION-------------------    -0
ENTIRE FINITE ELEMENT RESULTS OUTPUT---     1
THE NUMBER OF NODES IS-----------------   132
THE NUMBER OF ELEMENTS IS--------------   107
THE NUMBER OF BOUNDARY CONDITIONS IS---    49
```

```
* * * * * * FOR MESH GENERATION OF * * * * * *

     INCLUDE INTERFACE ELEMENTS FOR FRICTION = 0.1

THE NUMBER OF DATA ERRORS IS-----------      0

THE NUMBER OF SOIL MATERIALS IS--------      1

THE NUMBER OF PIPE MATERIALS IS--------     10

THE NUMBER OF INTERFACE MATERIALS IS---     11

THE BAND WIDTH IS----------------------     46

* * * * * * * MESH DATA HAS BEEN SAVED * * * * * * *

           AN ORDERED LIST OF BEAM ELEMENTS AROUND PIPE.
           ORDERING IS CLOCKWISE FROM TOP TO BOTTOM OR LEFT TO RITE.

             1    2    3    4    5    6    7    8    9   10
```

MATERIAL CHARACTERIZATION FOR SOILS.

PROPERTIES FOR MATERIAL 1 ******** HOMOGENEOUS SOIL

DENSITY = .12000E+03

YOUNGS MODULUS= .1000E+04
POISSONS RATIO= .3500E+00
CONFINED MOD.= .1605E+04
LATERAL COEFF.= .5385E+00

INTERFACE ELEMENT MATERIAL-GROUP PROPERTIES

MAT. NO.	NORMAL-ANGLE	COEF-FRICTION	TENSILE-RUPTURE
1	-90.00000	.10000	.00000
2	-72.00000	.10000	.00000
3	-54.00000	.10000	.00000
4	-36.00000	.10000	.00000
5	-18.00000	.10000	.00000
6	0.00000	.10000	.00000
7	18.00000	.10000	.00000
8	36.00000	.10000	.00000
9	54.00000	.10000	.00000
10	72.00000	.10000	.00000
11	90.00000	.10000	.00000

STRUCTURAL RESPONSES OF CULVERT   LOAD STEP = 1

X-COORD. / Y-COORD.	X-DISP. / Y-DISP.	N-PRES. / S-PRES.	MOMENT / M-STRESS	THRUST / T-STRESS	SHEAR / S-STRESS
0.00	0.	-.166E+02	.301E+02	-.392E+03	0.
24.25	-.156E+01	0.	.723E+03	-.783E+03	0.
7.49	.350E-02	-.168E+02	.237E+02	-.403E+03	.140E+01
23.06	-.152E+01	-.168E+01	.569E+03	-.806E+03	.280E+01
14.25	.521E-01	-.172E+02	.885E+01	-.417E+03	.200E+01
19.62	-.141E+01	-.172E+01	.212E+03	-.834E+03	.401E+01
19.62	.150E+00	-.178E+02	-.670E+01	-.431E+03	.222E+01
14.25	-.131E+01	-.178E+01	-.161E+03	-.862E+03	.443E+01
23.06	.254E+00	-.182E+02	-.248E+02	-.445E+03	.157E+01
7.49	-.125E+01	-.182E+01	-.595E+03	-.891E+03	.313E+01
24.25	.300E+00	-.188E+02	-.305E+02	-.460E+03	.453E-01
0.00	-.124E+01	-.188E+01	-.731E+03	-.920E+03	.907E-01
23.06	.259E+00	-.188E+02	-.255E+02	-.460E+03	-.131E+01
-7.50	-.123E+01	.188E+01	-.611E+03	-.919E+03	-.262E+01
19.62	.156E+00	-.182E+02	-.106E+02	-.445E+03	-.234E+01
-14.26	-.117E+01	.182E+01	-.253E+03	-.890E+03	-.468E+01
14.25	.545E-01	-.178E+02	.100E+02	-.430E+03	-.234E+01
-19.62	-.107E+01	.178E+01	.240E+03	-.860E+03	-.467E+01
7.49	.363E-02	-.173E+02	.249E+02	-.416E+03	-.139E+01
-23.06	-.959E+00	.173E+01	.597E+03	-.832E+03	-.278E+01
0.00	0.	-.171E+02	.311E+02	-.404E+03	0.
-24.25	-.913E+00	0.	.746E+03	-.808E+03	0.

```
CALCULATED SAFETY FACTORS AT STEP  1

     DISPLACEMENT ......... (DIAMETER*0.2/MAX-DISP.) =      15.00

     OUTER-FIBER STRESS ... (ULTIMATE / MAXIMUM)     =      15.01

     ELASTIC BUCKLING ....... (P-CRITICAL/P-AVERAGE) =       3.70

PERFORMANCE FACTORS

     HANDELING ...................... (FF*E*I/D**2) =       2.36
```

Problem 5 — Input

```
                 INPUT CARDS FOR PROBLEM NUMBER  5

CARD TYPE        1...+...10....+...20....+...30....+...40....+...50....+...60....+...70....+...80

  CARD 1A        DESI   2 ALUMIN TRENCH DEPTH 9 FEET, TRENCH WIDTH 7 FEET, OVERFILL 15 FEET
  CARD 1B           2    60.0
  CARD 2B              2.5         4.0         2.0         2.0
  CARD 1C        TREN       MODIFY LEVEL 2 FOR CONCENTRATED STRIP LOAD = 400LBS/IN (TOTAL)       MOD
  CARD 2C           1    1         -1                      15.0      120.0
  CARD 3C                               9.0        7.0
  CARD 4C           0    0    1
  CARD 7C         103                        -200.0                  1
  CARD 1D           1    1          INSITU (LINEAR)
  CARD 2D         1000.0   0.35
  CARD 1D           2    1          BEDDING = INSITU
  CARD 2D         1000.0   0.35
  CARD 1D        L  3    1  120.0   TRENCH FILL = 1500
  CARD 2D         1500.0   0.35
```

Problem 5 — Output

```
*** PROBLEM NUMBER  5 ***

TRENCH DEPTH 9 FEET, TRENCH WIDTH 7 FEET, OVERFILL 15 FEET

 EXECUTION MODE .....DESI

 SOLUTION LEVEL .....F.E.AUTO

 CULVERT TYPE ...... ALUMINUM


 PIPE PROPERTIES ARE AS FOLLOWS ...

      AVERAGE PIPE DIAMETER (IN.) ........     .60000E+02

      YOUNGS MODULUS OF PIPE (PSI) ......      .10200E+08

      POISSONS RATIO OF PIPE (-) ........      .33000E+00

      YIELD STRESS OF PIPE (PSI) ........      .24000E+05

      RUPTURE STRAIN OF PIPE (IN/IN) ....      .50000E-01

      DENSITY OF PIPE (PCI) .............    -0.

      MATERIAL CHARACTER, NONLIN ........    2
        NONLIN=0, IMPLIES LINEAR
        NONLIN=1, IMPLIES YIELD-HINGE
        NONLIN=2, IMPLIES BILINEAR CURVE

      MODULUS OF UPPER BI-CURVE .........      .60000E+06


 DESIRED SAFETY FACTORS FOR PIPE DESIGN ...

      THRUST STRESS YIELDING ............    2.50000

      DEFLECTION COLLAPSE,(0.2*D) .......    4.00000

      ELASTIC BUCKLING ..................    2.00000

      OUTER FIBER RUPTURE ...............    2.00000
```

```
* * BEGIN GENERATION OF CANNED MESH * *

THE DATA TO BE RUN IS ENTITLED

     MODIFY LEVEL 2 FOR CONCENTRATED STRIP LOAD = 800LBS/IN (TOTAL)

TYPE OF MESH------------------------- TRENCH

PLOTTING DATA SAVED------------------     1

PRINT SOIL RESPONSES-----------------     1

PRINT CONTROL FOR PREP OUTPUT----------  -0

NUMBER OF CONSTRUCTION INCREMENTS------   1

PIPE DIAMETER RATIO-------------------    1.00

LIVE LOAD PRESSURE ON LAST INCR.------   -0.00

DEPTH OF TRENCH-----------------------    9.00

WIDTH OF TRENCH-----------------------    7.00

SOIL HEIGHT ABOVE SPRINGLINE (FEET)----  21.50

MESH HEIGHT ABOVE SPRINGLINE (FEET)----   6.50

SOIL DENSITY ABOVE MESH (PCF)---------- 120.00

PRESSURE OF TRUNCATED SOIL (PSI)-------  12.50


IDENTIFICATION OF MATERIAL ZONE WITH MATERIAL NUMBERS.

          MATERIAL-ZONE    MATERIAL NO.

               INSITU       1
               BEDDING      2
               TRENCH       3
```

```
* * BEGIN PREP OF FINITE ELEMENT INPUT * *

THE DATA TO BE RUN IS ENTITLED

     MODIFY LEVEL 2 FOR CONCENTRATED STRIP LOAD = 400LBS/IN (TOTAL)

NUMBER OF CONSTRUCTION INCREMENTS------     1
PRINT CONTROL FOR PREP OUTPUT----------    -0
INPUT DATA CHECK-----------------------     0
PLOT TAPE GENERATION-------------------     1
ENTIRE FINITE ELEMENT RESULTS OUTPUT---     1
THE NUMBER OF NODES IS-----------------   110
THE NUMBER OF ELEMENTS IS--------------    96
THE NUMBER OF BOUNDARY CONDITIONS IS---    45
```

```
* * * CHANGES TO STANDARD LEVEL 2 MESH * * * *
* NUMBER OF NODES TO BE CHANGED -------        0*
* NUMBER OF ELEMENTS TO BE CHANGED ----        0*
* ADDITIONAL BOUNDARY CONDITIONS ------        1*
* * * * * * * * * * * * * * * * * * *  * * * *
```

```
***ADDITIONAL BOUNDARY CONDITIONS...FORCES = LBS  , DISPLACEMENTS = INCHES...

BOUNDARY       LOAD       X-FORCE       OR        Y-FORCE       OR          X-Y ROTATION
    NODE       STEP       X-DISPLACEMENT          Y-DISPLACEMENT                DEGREES

     103          1    F =  -0.              F =     -.2000E+03         -0.
```

```
* * * * * * FOR MESH GENERATION OF * * * * * *

    MODIFY LEVEL 2 FOR CONCENTRATED STRIP LOAD = 400LBS/IN (TOTAL)

THE NUMBER OF DATA ERRORS IS-----------     0
THE NUMBER OF SOIL MATERIALS IS--------     3
THE NUMBER OF PIPE MATERIALS IS--------    10
THE NUMBER OF INTERFACE MATERIALS IS---     0
THE BAND WIDTH IS----------------------    26
* * * * * * * MESH DATA HAS BEEN SAVED * * * * * * *

          AN ORDERED LIST OF BEAM ELEMENTS AROUND PIPE,
          ORDERING IS CLOCKWISE FROM TOP TO BOTTOM OR LEFT TO RITE.

            1    2    3    4    5    6    7    8    9   10
```

```
MATERIAL CHARACTERIZATION FOR SOILS.


PROPERTIES FOR MATERIAL  1    ******** INSITU (LINEAR)

     DENSITY =    =0.

      YOUNGS MODULUS=  .1000E+04
      POISSONS RATIO=  .3500E+00
      CONFINED MOD.=   .1605E+04
      LATERAL COEFF.=  .5385E+00


PROPERTIES FOR MATERIAL  2    ******** BEDDING = INSITU

     DENSITY =    =0.

      YOUNGS MODULUS=  .1000E+04
      POISSONS RATIO=  .3500E+00
      CONFINED MOD.=   .1605E+04
      LATERAL COEFF.=  .5385E+00


PROPERTIES FOR MATERIAL  3    ******** TRENCH FILL = 1500

     DENSITY =       .12000E+03

      YOUNGS MODULUS=  .1500E+04
      POISSONS RATIO=  .3500E+00
      CONFINED MOD.=   .2407E+04
      LATERAL COEFF.=  .5385E+00
```

```
DESIGN RESULTS AT  2 ITERATIONS

     *** REQUIRED THRUST AREA .........    .06965

     *** REQUIRED MOM. OR INERTIA .....    .00392

     *** REQUIRED SECTION MODULUS .....    .01067


THE FOLLOWING ALUMINUM CORRUGATED SECTIONS MEET THE
ABOVE REQUIREMENTS WITH MINIMUM AREA

     CORRUGATION    GAGE    THRUST AREA    MOM. INERTIA

       8/3 X  1/2     10         .14533          .00453
         3 X  1       16         .07416          .00865
         6 X  1       14         .08080          .01060
         6 X  2        8         .20408          .09616
         9 X  5/2      0         .11700          .09100


THE CORRUGATION WITH MINIMUM AREA AND
MOMENT OF INERTIA IS   3 X  1   GAGE, 16
AN ANALYSIS OF THIS CORRUGATION FOLLOWS.
```

STRUCTURAL RESPONSES OF CULVERT   LOAD STEP = 1

X-COORD. Y-COORD.	X-DISP. Y-DISP.	N-PRES. S-PRES.	MOMENT M-STRESS	THRUST T-STRESS	SHEAR S-STRESS
0.00	0.	-.109E+02	.182E+03	-.285E+03	0.
30.00	-.176E+01	0.	.111E+05	-.385E+04	0.
9.27	.817E-02	-.118E+02	.125E+03	-.337E+03	.867E+01
28.53	-.169E+01	-.968E+01	.767E+04	-.454E+04	.117E+03
17.63	.845E-01	-.148E+02	.157E+02	-.452E+03	.100E+02
24.27	-.153E+01	-.139E+02	.115E+04	-.610E+04	.135E+03
24.27	.220E+00	-.190E+02	-.631E+02	-.577E+03	.769E+01
17.63	-.138E+01	-.117E+02	-.386E+04	-.778E+04	.104E+03
28.53	.344E+00	-.213E+02	-.126E+03	-.661E+03	.337E+01
9.27	-.131E+01	-.557E+01	-.769E+04	-.891E+04	.455E+02
30.00	.383E+00	-.217E+02	-.126E+03	-.671E+03	-.301E+01
0.00	-.130E+01	.349E+01	-.774E+04	-.905E+04	-.405E+02
28.53	.322E+00	-.210E+02	-.692E+02	-.608E+03	-.238E+01
-9.28	-.128E+01	.954E+01	-.424E+04	-.820E+04	-.321E+02
24.27	.205E+00	-.155E+02	-.817E+02	-.510E+03	-.564E+01
-17.64	-.121E+01	.108E+02	-.500E+04	-.688E+04	-.761E+02
17.63	.754E-01	-.140E+02	.367E+02	-.408E+03	-.109E+02
-24.27	-.108E+01	.101E+02	.225E+04	-.551E+04	-.147E+03
9.27	.620E-02	-.117E+02	.123E+03	-.331E+03	-.571E+01
-28.53	-.933E+00	.573E+01	.751E+04	-.446E+04	-.769E+02
0.00	0.	-.106E+02	.144E+03	-.298E+03	0.
-30.00	-.872E+00	0.	.880E+04	-.402E+04	0.

Problem 5 — Output (cont'd)

NONLINEAR CHARACTERISTICS, LOAD STEP = 1

NODE	INNER-FIBER STRAIN	OUTER-FIBER STRAIN	STRAIN RATIO MAX-TO-YIELD	FRACTION OF WALL YIELDED
1	.63475E-03	-.13066E-02	.62319	0.00000
2	.27285E-03	-.10669E-02	.50887	0.00000
3	-.43255E-03	-.63269E-03	.30175	0.00000
4	-.10168E-02	-.34237E-03	.48494	0.00000
5	-.14505E-02	-.10563E-03	.69178	0.00000
6	-.14660E-02	-.11449E-03	.69919	0.00000
7	-.10863E-02	-.34518E-03	.51811	0.00000
8	-.10376E-02	-.16415E-03	.49439	0.00000
9	-.28466E-03	-.67735E-03	.32306	0.00000
10	.26663E-03	-.10455E-02	.49866	0.00000
11	.41737E-03	-.11204E-02	.53436	0.00000

Problem 5 — Output (cont'd)

```
CALCULATED SAFETY FACTORS AT STEP  1

     THRUST STRESS ....... (YIELD-STRESS/MAX-STRESS) =      2.65
     DISPLACEMENT ......... (DIAMETER*0.2/MAX-DISP.) =     13.55
     ELASTIC BUCKLING ....... (P-CRITICAL/P-AVERAGE) =      7.57
     STRAIN RUPTURE .... (RUPTURE-STRAIN/MAX-STRAIN) =     34.11

PERFORMANCE FACTORS

     BENDING STRESS ...... (YIELD-STRESS/MAX-STRESS) =      2.16
     HANDLING REQUIREMENT ............. (FF*EI/D**2) =      2.21
```

Problem 6 — Input

```
            INPUT CARDS FOR PROBLEM NUMBER  6

CARD TYPE   1...+...10....+...20....+...30....+...40....+...50....+...60....+...70....+...80

CARD 1A     ANALYS 3 CONCRE    D LOAD TEST, 60-INCH DIA., CLASS 3, WALL A.              1011
CARD 1B           60.0       5.0 CIRC    3
CARD 2B          4000.
CARD 3B        0.03666    0.0275       1.0       1.0
CARD 1C     PREP     D LOAD TEST
CARD 2C         6    4                  11   10    7
CARD 3C         1            0.0       30.0
CARD 3C         6    2      30.0       0.0                         -30.0
CARD 3C     L  11    2        0.0     -30.0                         -30.0
CARD 4C         1    2    1              1
CARD 4C         2    3    2              2
CARD 4C         3    4    3              3
CARD 4C         4    5    4              4
CARD 4C         5    6    5              5
CARD 4C         6    7    6              6
CARD 4C         7    8    7              7
CARD 4C         8    9    8              8
CARD 4C         9   10    9              9
CARD 4C     L  10   11   10             10
CARD 5C         1    1                    -75.0              1
CARD 5C         1    1                    -75.0              2
CARD 5C         1    1                    -75.0              3
CARD 5C         1    1                    -75.0              4
CARD 5C         1    1                    -75.0              5
CARD 5C         1    1                    -75.0              6
CARD 5C     L  11    1              1                        1
CARD 1D     L   1    1
CARD 2D            0.0       0.0
```

Problem 6 — Output

```
*** PROBLEM NUMBER  6 ***

  D LOAD TEST, 60-INCH DIA., CLASS 3, WALL A.

EXECUTION MODE .....ANAL

SOLUTION LEVEL .....F.E.USER

CULVERT TYPE ...... CONCRETE
```

```
PIPE PROPERTIES ARE AS FOLLOWS ...
(UNITS ARE INCH-POUND SYSTEM )

     NOMINAL PIPE DIAMETER ..............          60.0000

     CONCRETE COMPRESSIVE STRENGTH .....         4000.0000

     CONCRETE ELASTIC MODULUS ..........      3834253.5127

     CONCRETE POISSON RATIO ............             .1700

     STEEL YIELD STRENGTH ..............        40000.0000

     STEEL ELASTIC MODULUS .............     29000000.0000

     STEEL POISSON RATIO ...............             .3000

     NONLINEAR CODE (1,2,OR 3) .........                 3

     CONC. CRACKING STRAIN (1,2,3) .....          0.000000

     CONC. YIELDING STRAIN (2,3) .......           .000507

     CONC. CRUSHING STRAIN (2,3) .......           .002000

     STEEL YIELDING STRAIN (3) .........           .001255

     WALL THICKNESS ....................            5.0000

     SHAPE OF REBAR CAGES ..............              CIRC

     INNER CAGE STEEL AREA .............             .0367

     OUTER CAGE STEEL AREA .............             .0275

     COVER TO CENTER OF INNER REBAR ....            1.0000

     COVER TO CENTER OF OUTER REBAR ....            1.0000
```

```
* * BEGIN PREP OF FINITE ELEMENT INPUT * *

THE DATA TO BE RUN IS ENTITLED

    D LOAD TEST

NUMBER OF CONSTRUCTION INCREMENTS------       6
PRINT CONTROL FOR PREP OUTPUT----------       4
INPUT DATA CHECK-----------------------      =0
PLOT TAPE GENERATION-------------------      =0
ENTIRE FINITE ELEMENT RESULTS OUTPUT---      =0
THE NUMBER OF NODES IS-----------------      11
THE NUMBER OF ELEMENTS IS--------------      10
THE NUMBER OF BOUNDARY CONDITIONS IS---       7
```

```
* * * * * * FOR MESH GENERATION OF * * * * * *

    D LOAD TEST

THE NUMBER OF DATA ERRORS IS-----------     0
THE NUMBER OF SOIL MATERIALS IS--------     0
THE NUMBER OF PIPE MATERIALS IS--------    10
THE NUMBER OF INTERFACE MATERIALS IS---     0
THE BAND WIDTH IS----------------------     4
* * * * * * * MESH DATA HAS BEEN SAVED * * * * * * *

          AN ORDERED LIST OF BEAM ELEMENTS AROUND PIPE.
          ORDERING IS CLOCKWISE FROM TOP TO BOTTOM OR LEFT TO RITE.

             1    2    3    4    5    6    7    8    9   10
```

```
MATERIAL CHARACTERIZATION FOR SOILS.


PROPERTIES FOR MATERIAL  1    ********

     DENSITY =    -0.

      YOUNGS MODULUS= 0.
      POISSONS RATIO= 0.
      CONFINED MOD.=  0.
      LATERAL COEFF.= 0.


WARNING MORE MATERIAS WERE INPUT THAN DEFINED    1    0
```

Problem 6 – Output (cont'd)

STRUCTURAL RESPONSE OF CULVERT FOR LOAD INCREMENT 1

COORDINATES, DISPLACEMENTS AND CRACK DEPTHS ARE IN INCHES
PRESSURES ARE IN LB/IN**2
MOMENTS ARE IN IN.*LB/IN.
THRUST AND SHEAR ARE IN LB/IN.

NPPT	X-COORD. / Y-COORD.	X-DISP. / Y-DISP.	N-PRES. / S-PRES.	MOMENT / THRUST	SHEAR / CRACK DEPTH
1	0.00	0.	-.15981E+02	.14849E+04	0.
	30.00	-.56649E-01	0.	.32014E-09	.37592E+01
2	9.27	.73843E-03	-.23699E-11	.78962E+03	.70451E+02
	28.53	-.51887E-01	-.21555E-10	-.22891E+02	.37112E+01
3	17.63	.56718E-02	-.21808E-10	.16239E+03	.59929E+02
	24.27	-.42121E-01	-.16802E-10	-.43541E+02	.33224E+01
4	24.27	.14348E-01	.22484E-10	-.33538E+03	.43541E+02
	17.63	-.33361E-01	-.46256E-13	-.59929E+02	.36497E+01
5	28.53	.22762E-01	-.10398E-10	-.65497E+03	.22891E+02
	9.27	-.28973E-01	-.26983E-10	-.70451E+02	.37423E+01
6	30.00	.26215E-01	-.60396E-11	-.76509E+03	-.49459E-11
	0.00	-.28325E-01	-.71220E-11	-.74077E+02	.37566E+01
7	28.53	.22762E-01	-.14736E-10	-.65497E+03	-.22891E+02
	-9.27	-.27676E-01	-.15787E-11	-.70451E+02	.37423E+01
8	24.27	.14348E-01	-.76089E-11	-.33538E+03	-.43541E+02
	-17.63	-.23288E-01	-.73727E-12	-.59929E+02	.36497E+01
9	17.63	.56718E-02	-.85803E-11	.16239E+03	-.59929E+02
	-24.27	-.14528E-01	.59944E-11	-.43541E+02	.33224E+01
10	9.27	.73843E-03	-.50497E-12	.78962E+03	-.70451E+02
	-28.53	-.47627E-02	.59715E-11	-.22891E+02	.37112E+01
11	0.00	0.	-.15981E+02	.14849E+04	0.
	-30.00	0.	0.	-.17553E-09	.37592E+01

Problem 6 — Output (cont'd)

STRESSES IN CULVERT WALL (PSI) FOR LOAD INCREMENT 1

NPPT	ELLIP, OR INNER CAGE STEEL	OUTER CAGE STEEL	CONCRETE COMPRESSION	SHEAR STRESS
1	.11400E+05	-.99485E+03	-.63517E+03	0.
2	.59567E+04	-.63439E+03	-.35080E+03	.19852E+02
3	.10129E+04	-.29549E+03	-.90645E+02	.18046E+02
4	-.40958E+03	.30976E+04	-.19559E+03	.10854E+01
5	-.58875E+03	.62640E+04	-.35595E+03	.39513E+00
6	-.64953E+03	.73564E+04	-.41111E+03	-.80885E-13
7	-.58875E+03	.62640E+04	-.35595E+03	-.39513E+00
8	-.40958E+03	.30976E+04	-.19559E+03	-.10554E+01
9	.10129E+04	-.29549E+03	-.90645E+02	-.18046E+02
10	.59567E+04	-.63439E+03	-.35080E+03	-.19852E+02
11	.11400E+05	-.99485E+03	-.63517E+03	0.

Problem 6 — Output (cont'd)

```
CALCULATED SAFETY FACTORS FOR LOAD INCREMENT     1

     STEEL YIELD STRESS / MAX. STEEL STRESS .........      3.509
     CONCRETE STRENGTH / MAX. COMPRESSIVE STRESS ....      6.298
     WALL SHEAR CAPACITY / MAX. SHEAR ...............     15.929
PERFORMANCE FACTORS
     0.01 INCH / MAX. CRACK WIDTH ...................      3.809
     ALLOWABLE DISPLACEMENT(LUM) / MAX. DISP. .......     10.591
     TENSILE STRENGTH / STRESS FROM BOW STRING ......      2.059
```

STRUCTURAL RESPONSE OF CULVERT FOR LOAD INCREMENT 2

COORDINATES, DISPLACEMENTS AND CRACK DEPTHS ARE IN INCHES
PRESSURES ARE IN LB/IN**2
MOMENTS ARE IN IN.*LB/IN.
THRUST AND SHEAR ARE IN LB/IN.

NPPT	X-COORD. Y-COORD.	X-DISP. Y-DISP.	N-PRES. S-PRES.	MOMENT THRUST	SHEAR CRACK DEPTH
1	0.00 30.00	0. -.11340E+00	-.31962E+02 0.	.29689E+04 .10477E-08	0. .37593E+01
2	9.27 28.53	.14761E-02 -.10388E+00	-.13130E-10 -.42371E-10	.15783E+04 -.45782E+02	.14090E+03 .37113E+01
3	17.63 24.27	.11349E-01 -.84326E-01	-.17253E-10 -.25710E-10	.32387E+03 -.87082E+02	.11986E+03 .33372E+01
4	24.27 17.63	.28722E-01 -.66779E-01	.27975E-10 -.42603E-10	-.67167E+03 -.11986E+03	.87082E+02 .36501E+01
5	28.53 9.27	.45563E-01 -.57998E-01	-.19354E-10 -.78378E-10	-.13109E+04 -.14090E+03	.45782E+02 .37424E+01
6	30.00 0.00	.52473E-01 -.56699E-01	-.13592E-10 -.25872E-10	-.15311E+04 -.14815E+03	.15029E-09 .37568E+01
7	28.53 -9.27	.45563E-01 -.55399E-01	-.27185E-10 -.15965E-10	-.13109E+04 -.14090E+03	-.45782E+02 .37424E+01
8	24.27 -17.63	.28722E-01 -.46618E-01	-.17399E-10 -.47363E-11	-.67167E+03 -.11986E+03	-.87082E+02 .36501E+01
9	17.63 -24.27	.11349E-01 -.29073E-01	-.14370E-10 .17148E-10	.32387E+03 -.87082E+02	-.11986E+03 .33372E+01
10	9.27 -28.53	.14761E-02 -.95220E-02	.44391E-12 .10146E-10	.15783E+04 -.45782E+02	-.14090E+03 .37113E+01
11	0.00 -30.00	0. 0.	-.31962E+02 0.	.29689E+04 -.53751E-09	0. .37593E+01

STRESSES IN CULVERT WALL (PSI) FOR LOAD INCREMENT 2

NPPT	ELLIP. OR INNER CAGE STEEL	OUTER CAGE STEEL	CONCRETE COMPRESSION	SHEAR STRESS
1	.22794E+05	-.19887E+04	-.12699E+04	0.
2	.11907E+05	-.12679E+04	-.70119E+03	.39704E+02
3	.20610E+04	-.58449E+03	-.18167E+03	.35960E+02
4	-.81901E+03	.62024E+04	-.39145E+03	.21674E+01
5	-.11777E+04	.12539E+05	-.71238E+03	.78977E+00
6	-.12991E+04	.14724E+05	-.82268E+03	.24568E-11
7	-.11777E+04	.12539E+05	-.71238E+03	-.78977E+00
8	-.81901E+03	.62024E+04	-.39145E+03	-.21674E+01
9	.20610E+04	-.58449E+03	-.18167E+03	-.35960E+02
10	.11907E+05	-.12679E+04	-.70119E+03	-.39704E+02
11	.22794E+05	-.19887E+04	-.12699E+04	0.

```
CALCULATED SAFETY FACTORS FOR LOAD INCREMENT     2

     STEEL YIELD STRESS / MAX. STEEL STRESS .........        1.755
     CONCRETE STRENGTH / MAX. COMPRESSIVE STRESS ....        3.150
     WALL SHEAR CAPACITY / MAX. SHEAR ...............        7.965
PERFORMANCE FACTORS
     0.01 INCH / MAX. CRACK WIDTH ...................        1.384
     ALLOWABLE DISPLACEMENT(LUM) / MAX. DISP. .......        5.291
     TENSILE STRENGTH / STRESS FROM BOW STRING ......        1.230
```

STRUCTURAL RESPONSE OF CULVERT FOR LOAD INCREMENT 3

COORDINATES, DISPLACEMENTS AND CRACK DEPTHS ARE IN INCHES
PRESSURES ARE IN LB/IN**2
MOMENTS ARE IN IN.*LB/IN.
THRUST AND SHEAR ARE IN LB/IN.

NPPT	X-COORD. / Y-COORD.	X-DISP. / Y-DISP.	N-PRES. / S-PRES.	MOMENT / THRUST	SHEAR / CRACK DEPTH
1	0.00	0.	-.47943E+02	.44529E+04	0.
	30.00	-.17015E+00	0.	.17753E-08	.37593E+01
2	9.27	.22138E-02	.76453E-12	.23670E+04	.21135E+03
	28.53	-.15587E+00	-.68830E-10	-.68673E+02	.37113E+01
3	17.63	.17027E-01	-.26268E-10	.48533E+03	.17979E+03
	24.27	-.12653E+00	-.47591E-10	-.13062E+03	.33421E+01
4	24.27	.43096E-01	.23147E-10	-.10080E+04	.13062E+03
	17.63	-.10020E+00	-.76944E-10	-.17979E+03	.36502E+01
5	28.53	.68364E-01	-.15978E-10	-.19668E+04	.68673E+02
	9.27	-.87024E-01	-.83041E-10	-.21135E+03	.37425E+01
6	30.00	.78732E-01	-.19513E-10	-.22971E+04	.28467E-09
	0.00	-.85074E-01	-.64922E-10	-.22223E+03	.37568E+01
7	28.53	.68364E-01	-.43685E-10	-.19668E+04	-.68673E+02
	-9.27	-.83124E-01	-.23160E-10	-.21135E+03	.37425E+01
8	24.27	.43096E-01	-.16552E-10	-.10080E+04	-.13062E+03
	-17.63	-.69949E-01	.10252E-10	-.17979E+03	.36502E+01
9	17.63	.17027E-01	-.76177E-11	.48533E+03	-.17979E+03
	-24.27	-.43618E-01	.19189E-10	-.13062E+03	.33421E+01
10	9.27	.22138E-02	-.74976E-12	.23670E+04	-.21135E+03
	-28.53	-.14281E-01	.13998E-10	-.68673E+02	.37113E+01
11	0.00	0.	-.47943E+02	.44529E+04	0.
	-30.00	0.	0.	-.72669E-09	.37593E+01

Problem 6 — Output (cont'd)

STRESSES IN CULVERT WALL (PSI) FOR LOAD INCREMENT 3

NPPT	ELLIP. OR INNER CAGE STEEL	OUTER CAGE STEEL	CONCRETE COMPRESSION	SHEAR STRESS
1	.34188E+05	-.29825E+04	-.19046E+04	0.
2	.17857E+05	-.19013E+04	-.10516E+04	.59556E+02
3	.31098E+04	-.87350E+03	-.27273E+03	.53874E+02
4	-.12285E+04	.93075E+04	-.58733E+03	.32492E+01
5	-.17666E+04	.18813E+05	-.10688E+04	.11844E+01
6	-.19485E+04	.22091E+05	-.12343E+04	.46526E-11
7	-.17666E+04	.18813E+05	-.10688E+04	-.11844E+01
8	-.12285E+04	.93075E+04	-.58733E+03	-.32492E+01
9	.31098E+04	-.87350E+03	-.27273E+03	-.53874E+02
10	.17857E+05	-.19013E+04	-.10516E+04	-.59556E+02
11	.34188E+05	-.29825E+04	-.19046E+04	0.

```
CALCULATED SAFETY FACTORS FOR LOAD INCREMENT     3

     STEEL YIELD STRESS / MAX. STEEL STRESS .........      1.170
     CONCRETE STRENGTH / MAX. COMPRESSIVE STRESS ....      2.100
     WALL SHEAR CAPACITY / MAX. SHEAR ...............      5.310
PERFORMANCE FACTORS
     0.01 INCH / MAX. CRACK WIDTH ...................       .844
     ALLOWABLE DISPLACEMENT(LUM) / MAX. DISP. .......      3.526
     TENSILE STRENGTH / STRESS FROM BOW STRING ......       .820
```

FHWA
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